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DESIGN AND EVALUATION METHODS FOR UNDERWATER CONTROL SYSTEMS

MASTER

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TRONDHEIM

DR.

Doktorgrad ved NTNU

Fjernstyrte undervanns-systemer

Sivilingeniør *Chi Lin* (32) fra Beijing har tatt graden doktor ingeniør ved Norges teknisk-naturvitenskapelige universitet (NTNU) med en avhandling om optimal utvikling av styresystemer for fjernstyrte undervanns-systemer.

Chi Lins hypotese er at det gjennom en systematisk metodikk kan utvikles styresystemer som er mer optimale enn dagens, både fra en ergonomisk og en driftssikkerhetsmessig synsvinkel. Han beskriver de oppgavene som et undervanns styresystem må løse, og legger i første rekke vekt på styringsoppgaver for ulike typer verktøysystemer som er spesialbygget for definerte undervannsoperasjoner. Han tar så for seg en del prinsipper for utforming av styresystemer og vurderer hvilken relevans disse har for den aktuelle situasjon. Momenter fra for eksempel utforming av flycockpiter er tatt med.

Ut fra dette beskriver Chi Lin en metodikk for optimal spesifikasjon av styresystemene. Denne metodikken anvender han så som eksempel på en konkret utforming av styringen for et verktøysystem som bygges industrielt i dag.

Chi Lins arbeid gir ny innsikt i hvordan en styresystemoppgave kan spesifiseres ut fra en kartlegging og systematisk bearbeiding av alle data av funksjonell, ergonomisk og operasjonell karakter.

Avhandlingen har tittelen «Design og evalueringsmetoder for undervanns kontrollsystemer». Den er utført ved Institutt for produksjons- og kvalitetsteknikk, NTNU, og ved Kværner Energy AS med professor Terje K. Lien som hovedveileder.

Chi Lin ble utdannet ingenir ved Bicea, Beijing, i 1985, og sivilingeniør ved Fakultet for maskinteknikk, Norges tekniske høgskole, i 1991. Han er ansatt som senioringeniør ved Kværner Energy AS i Oslo.

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Design and Evaluation Methods for Underwater Control Systems

MASTER

Chi Lin
A dissertation submitted to
Department of Production and Quality Engineering
Norwegian University of Science and Technology
in partial fulfilment of the requirement for the degree of dr.ing.

Institutt for produksjons- og kvalitetsteknikk
Norges teknisk-naturvitenskapelige universitet

Trondheim, 1996

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To my dear wife, daughter and son

Preface and Acknowledgment

This dissertation has been carried out at the Business area Oil and Gas in Kværner Energy Group, Division Oslo.

During the time I am working with the dissertation, I have gotten help from a lot of people. I especially would like to thank my supervisor, Professor Terje K. Lien for those stimulating conversations, valuable ideas and important feedback during task forming and finalize the dissertation.

I am very grateful for the initiative from Chief Engineer Jan Erik Sylljeset and product manager Per Olav Halle about the needs of Ultra Deep water tie-in control system development. It is this proposal gave me the chance to work on a meaningful research project.

I would like to express my sincere gratitude to Ph.D Einar Kjellan-Fosterud and Tekn. lic. Christer Gustafsen. They have spent their precious time helping me reading through this thesis and correcting numerous errors. It is them that helped to increase readability of the dissertation, and made it more organized.

I would like to thank Senior Engineer Geir Julkestad and other engineers in tie-in equipment group for many of fruitful and creative discussions.

I would like to express my gratitude to my friends and colleagues Ph.D. Trygve Thomessen for the inspiring discussions and encouragement. Thanks to Ph.D student Kaj Johnson and my friend Henrik Vedeld for their help and friendship.

I would like to thank management in Oil and Gas Division for giving me permission to use real product as example.

I would like to thank my local supervisors -- Chief Engineer Jan Erik Sylljeset in Oil and Gas division and Director Kjell Rogstad in Hydropower division for the helps in day to day practical problems.

The financial supports of this dissertation are from two sources, among them are two years part time work for Oil and Gas division and one year part time work for Hydropower division. I would like to thank the managements in both of these divisions for their generous support and the chance to work for them.

I would like to thank the support and encouragement from our families, they have been invaluable treasure for me.

At last I would like to thank my beloved wife, without the full support from her the dissertation will be an impossible task to complete. The distraction from my lovely daughter and son made me relax after a hard long day, so I can return to this endless work and finally complete it.

Purpose of thesis

In many areas of technology, there are standards or recommended practices, but for underwater working equipment, there has not ready made standard yet. NORSOK and ISO are working on a standard for Intervention equipment, but they are far from a guidance for designer for such equipment.

Many engineers want to have a design method, and a method for evaluation design problem, Many experienced engineers know how to make a good design, but could not tell other. At many instances no expert is available.

The development of design and evaluation method is a complicated work, since it involves many different factors and principles, and many of the topics belong to different area. My main challenge was the way to organize studies that covers different areas, and to make them useful as a guidance for the engineer working with underwater system,.

The thesis summarized techniques and models that can be used in a control system design with special analysis towards characteristics of underwater system. Developed techniques for evaluate underwater control system with special concern to system operator in both physical and psychological aspects.

The thesis organizes different aspects related to design and evaluation method in an orderly manner, to present the reader a clear procedure of how to generate good conceptual of control system, and how to evaluate generated concepts and designs. One real product was used as an example to show how the methods and techniques can be used.

Organization of thesis

This thesis is written with the designer mind, some knowledge of control theory is assumed.

To help the readers to get better understanding of the system they are going to deal with, the thesis is organized in a stepwise structure. The reader will gain the basic knowledge about underwater tasks, equipment and control systems. Afterwards, the reader will be able to follow the steps to develop a required control system for an underwater equipment, by first understanding the characteristics of design problem, customer requirement, functional requirement and possible solution, then if needed presents the control problem in a form of mathematics model. After the concept is developed, a procedure is guiding the reader to develop a set of evaluation criteria and different ways to make the decision.

This thesis does not give the techniques required for making a detailed control system design, but an overview of the way to make a successful design.

The thesis consists of the following chapters:

Chapter 1

Describes of classification of underwater operations and systems.

Chapter 2

Describes issues concerning underwater control system and control method.

Chapter 3

Describes design method and control systems theory with focuses on human centered control.

Chapter 4

Describes methods used to evaluate and to rank products and their performance.

Chapter 5

Applies the foregoing methods to an example, Kværner Energy's PICT (Pull-In and Connection Tool). The whole process of concept development and evaluation of a concept design is illustrated in this chapter.

Application of thesis

The thesis can be used as a text book for undergraduate students and engineers who are interested in underwater working systems and corresponding control systems. It can also be used as a procedure for an underwater control concept design and evaluation.

Keywords

design method, evaluation method, underwater control system, tie-in, pull-in and connection

Table of Content

1 Underwater technology and systems

1.1 Underwater technology

Modern underwater technology began with the need for seabed surveying. Since the beginning in the 1950s new techniques have been developed, but the knoledge of seabed stratigraphy was poor even in the 1960s, when the offshore gas fields in the southern North Sea were built.

All potential fixed platform sites require to be surveyed with sufficient precision to ensure a flat even seabed for stability, and carry the concentrated load for subsea structure foundation. In more than one instance in the North Sea, operators have been faced with a last-minute change of site or a hurried clearance of boulders from a site because of insufficient information from initial surveys. These situations indicate the need not only for accurate underwater surveys but also for better underwater location and navigation techniques.

Seabed pipelines and cables also require precise underwater surveys, once a suitable line is selected, a geophysical survey for the underlying strata is conducted to determine the suitability of the seabed sediment for burying the pipeline. Another advantage of such a survey is that secure holding ground can be selected for anchoring the lay barge during construction. On completion, annual side scan sonar and sub-bottom profile surveys are required to check the depth of burial.

From the 1970s, after numerous failures, offshore oil companies began to realize the importance of underwater surveys of the sea floor and sub-seabed conditions before starting any offshore engineering work, such as platform installation, pipeline laying or semi-submersible anchoring. In general, the cost of such a survey is small relative to the possible danger and expense incurred as a result of a seabed collapse.

As exploration has ventured into deeper water, diving becomes more complicated or not feasible. The Offshore installations Regulations 1975 require than below 50 m a diving bell must be used. With increasing decompression times, saturation diving has become a necessity. To overcome the problems of decompression, the offshore industry has developed a variety of atmospheric diving suits, manned and unmanned submersibles for underwater surveying and inspection work.

In deep water diverless techniques become the preferred solution. Many of the underwater tasks require ROV(Remote Operated Vehicle) as primary or assistance working system. The general purpose ROV carries a range of information acquisition devices and advanced manipulators for object handling. Special designed underwater tooling systems have been made, such as high accuracy maintenance equipment, devices with reparation capability and override function, equipment with large lifting or pulling capacity. Many of the equipment were preliminary designed for installation work, for example, pipeline tie-in, platform tension leg tightening, etc.. Figure 1.1 shows a typical Subsea Intervention system operated from a ROV.

In the following sections, we are going to introduce a variety of underwater working systems, such as ROV, ROT, etc. The underwater production system is not within the scope of this thesis.

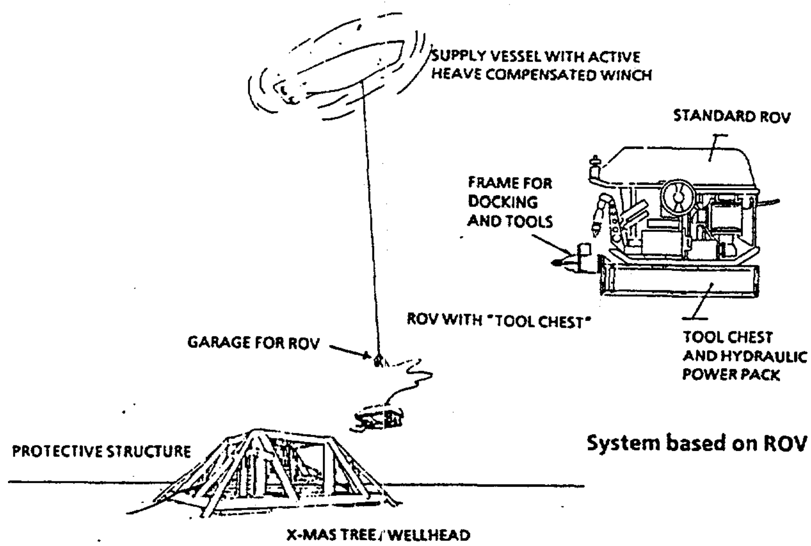


Figure 1.1 Typical Subsea Intervention System with ROV

1.1.1 *The definition of underwater task*

Underwater tasks consist a wide range of operations. Many of the tasks which could only be carried out onshore before, are also required to be accomplished in "wet" environment.

Table 1.1 classified eight different categories of the underwater tasks and manipulation requirement.

Table 1.1 The classification of underwater task

Tasks	Description	Complexity for manipulator operation
Scientific survey	Geological survey Geophysical survey	Not necessary
Site survey	Seabed contours Seabed composition Subsea obstructions	Simple or not necessary
Preparation	Route profiling Site leveling Site clearance Obstruction clearance Void filling	Simple Low accuracy (> 3 cm)
Inspection	Inspection during laying of pipelines/cables Inspection during burying of pipelines/cables Routine inspection Damage repair/inspection Inspection of structures, SPMs, Underwater storage tanks and seabed completion	Medium to Complex Normal accuracy (1 to 3 cm)
Installation and construction	Pipeline/cable trenching Anchorage and backfilling Reburial after repairs Installation of fixed structure and seabed completion Connection of pipelines and risers General underwater civil engineering work	Complex Normal accuracy (0.5 to 1 cm)
Repairs and replacement	Fixed structures Pipelines Risers Seabed completions Assistance during repairs X-mas Trees Valves	Complex Normal accuracy (0.5 to 1 cm) Force reflection recommended
Material handling	Underwater CNC system	Simple High accuracy (< 0.1cm)
	Sample collection	Simple, force feedback recommended
Training/rescue	Training of divers Rescue of divers Rescue of Equipment Underwater transport of divers and or equipment	Simple Low accuracy (> 3 cm)

Among them, scientific survey and site survey are comparable simple tasks from manipulation requirement point of view. The offshore industries generally pays more attention to the more demanding work like construction, inspection and maintenance. The following section contains descriptions of the underwater tasks mainly associated with offshore activities.

1.1.2 Typical offshore and underwater tasks

Typical offshore and underwater tasks besides site survey include preparation, inspection, installation and construction, repairs and maintenance.

1. Typical installation and construction work tasks

- Trenching for cables/pipes
- Lifting
- Pulling
- Bolt Handling
- Equipment Transport
- Sandbag Support
- Connection & disconnection
- Installation and cleaning of guide wires
- Bell handling
- Hyperbaric Welding

2. Typical Inspection tasks

- MPI (Magnetic Particle Inspection)
- Cleaning (for MPI)
- Grinding related to MPI
- Grinding related to other inspection
- Close Visual Inspection (CVI)
- Ultrasonic Scanning (US)
- Cleaning for CVI or US
- General Visual Inspection (GVI)
- Straight line measurement
- Crack Propagation Analysis
- Rigging related to inspection activities
- Install automatic US
- Photography/Photogrammetry
- Video recording
- Locate buried pipeline
- C.P. Readings
- Flooded Member Detection (FMD)
- Eddy Current Measurement
- Pipeline Survey

Figure 1.2 shows the typical ROV equipped with necessary equipment for cleaning task. Figure 1.3 is the typical ROV pipeline inspection configuration.

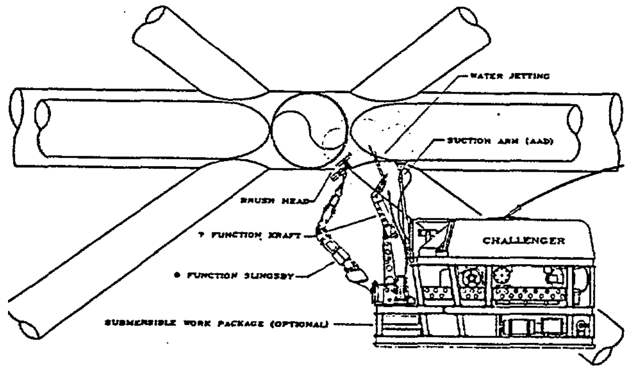


Figure 1.2 Platform Cleaning

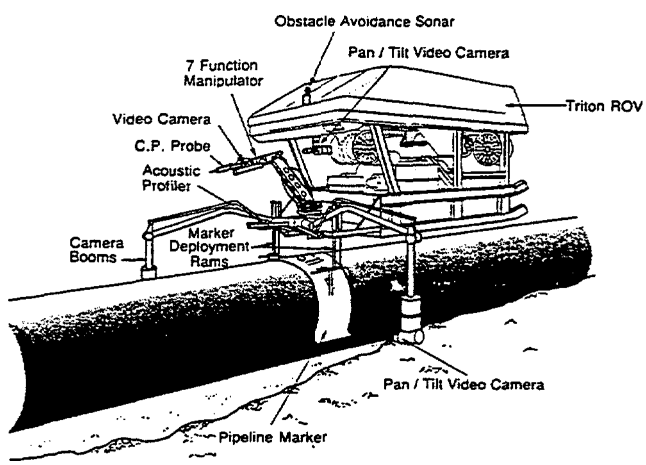


Figure 1.3 TRITON ROV pipeline inspection configuration

3. Typical Repair and Maintenance tasks

- Bulk cleaning
- Anode replacement
- Dredging
- Wellhead Intervention
- Replace/adjust valves
- Wellbay control modules replacement
- Manifold control modules replacement
- Filter modules replacement
- Operating valve actuators

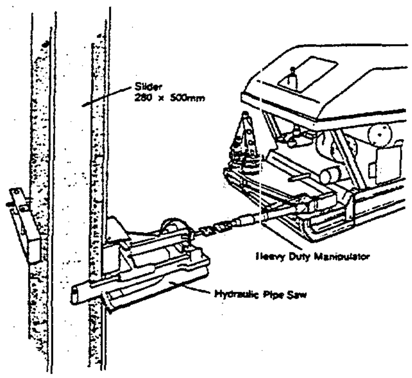


Figure 1.4 Remote removal of slider on structure

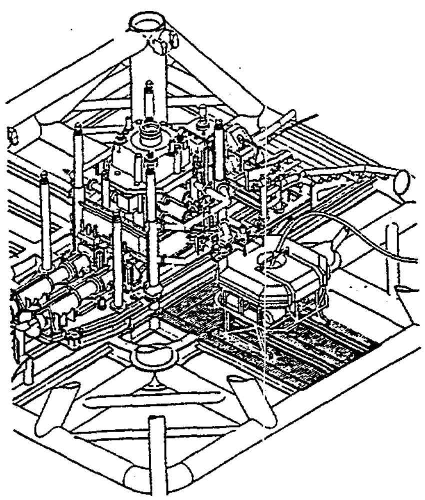


Figure 1.5 ROV Operating valve manual override

Figure 1.4 shows the configuration of remote removal of slider on an underwater structure, Figure 1.5 shows the ROV Operating manual valve on a production well.

1.1.3 Working objects

The most important underwater tasks associated with offshore business are applied on following structures and systems.

1) Pipeline (trunk-line)
2) Fixed platform
3) Offshore loading system
4) Subsea completion system

5) Other floating anchored system

We will now explain in each of working object a bit more in detail.

1. Pipeline:

The installing of pipeline includes construction (laying), inspection and repairing in case of damage.

1) Construction:

During the route survey, the pipeline route is marked up through areas with difficult bottom conditions.

During the pipe lay, the line is guided into the right position by lay-vessel maneuver, then the pipeline is the connected. Continuous inspection of the pipe immediately after the pipe touches down on the bottom is important, because this is the location of maximum material stress. The heavy pipe coating and the corrosion coating as well as the steel pipe itself may be severely damaged during the lay, so continuous inspection allows for immediately corrective measures to be taken. The burying of pipelines occurs afterwards. Before connecting of pipe lines, the laid pipes are aligned, many methods can be used to align pipes. Figure 1.6 shows one of the concept of pipeline alignment before connection.

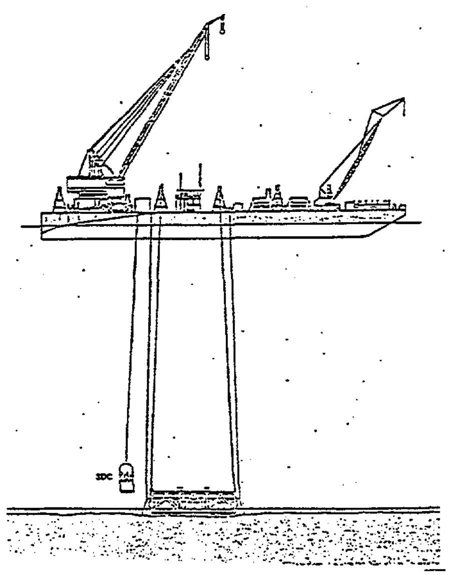


Figure 1.6 Pipeline alignment

2) Repair:

In order to locate the exact position of the crack or leak point, it is necessary to track a buried pipeline to find point of damage. If a damaged pipeline needs to be repaired, then it has to be uncovered if it is buried.

A repair operation will normally involve at least cutting and removing both coating and pipe segment. For the welded joints end preparation, welding and control will also have to be carried out. The corrosion protection must be re-established.

Figure 1.7 shows the pipeline repair operation with SPRV (submersible pipeline repair vehicle).

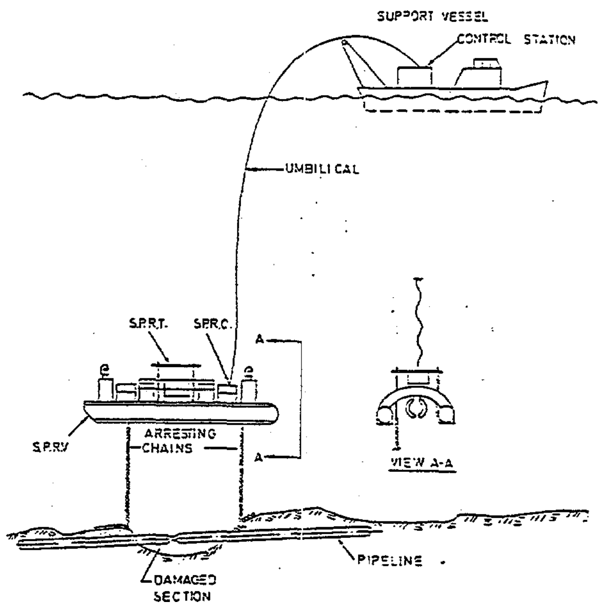


Figure 1.7 Pipeline repair

2. Fixed platform:

1) Construction

The fixed platforms normally have piled or gravity type structures. Before platform installation, the site is surveyed and verified that all obstacles is cleared at site.

2) Inspection requirement:

Regulations about regular surveys of fixed installations have in force since 1975. To satisfy the Regulations, a major survey must be carried out at intervals not exceeding 5 years. Additionally, an annual survey must be done to check on deterioration, but this can form a part of a continuous survey. In the event of damage or deterioration on platform being suspected, an additional survey may be required.

For a first or subsequent major survey the Guidance Notes specify:

(1) visual examination of the whole structure above and below water
(2) detailed visual examination of selected welds and of recorded repairs
(3) additional close inspection as the surveyor may judge necessary
(4) provision of further information to verify suspected damage or defect
(5) seabed-level inspection, particularly of score.
(6) survey and inspection of cathodic protection potential.

3) Repair:

Every platform repair is unique. The method of repair and the tools and equipment to be used will depend on the case one will be faced with. All kinds of platform structures, both steel and concrete, are very difficult to repair. Minor damage such as scaling off of concrete resulting in bare reinforcement, or minor cracking might occur. Repair of such damages require removal of marine growth, chipping, epoxy injection and/or placing of concrete mortar. More severe damages which a concrete structure may sustain e.g. knocking a hole in the structure.

Repair of a steel structure may involve cutting of steel members, replacement of these and connecting the new members to the structure preferably by welding, or by other means. Temporary stiffening may be necessary. Hyperbaric welding is probably the most attractive welding method. In many cases, local grinding can be used to remove small cracks or defects without requirement of welding, such a study has been carried out intensively in the Norwegian Institute of Technology and SINTEF.

3. Offshore Loading Systems:

The layout of these systems may differ a lot from concept to concept. As a consequence of this, the installation technique and the work involved varies from case to case. Some of the systems are of the anchored floating buoy or tank type. Others are of the bottom fixed tower type. A common feature of all these systems is that they have a submersible pipeline linking them to the production or storage unit. Linking the submersible pipe to the floating units is achieved by a flexible pipe. For the tie-in and connection work, divers or special designed machinery is required.

4. Subsea completion and production systems.

1) Construction

These types of systems are based on two different methods, the wet method and the dry method. These systems vary widely in layout from case to case. Figure 1.8 is a layout of a satellite system.

One production setup may consist of one or several single wellhead completions connected by underwater pipelines to a central production unit, which may be a underwater unit or a fixed or floating platform. Another setup is the multiple well manifold/production station.

The wet method leaves trees and systems exposed to the water. In the dry method, trees, valves, etc., are enclosed in a chamber which can have atmospheric pressure. The chambers are accessible for people who can do maintenance work under atmospheric conditions. The various layouts contain several underwater pipelines, some of them are flexible pipes.

Maintenance of these systems is based on different methods. Some are modularized and the modules are picked up and brought to the surface where the maintenance is carried out. Others use manipulators to carry out the replacement under atmospheric conditions inside the chamber or alternatively operated underwater by ROV or ROT directly.

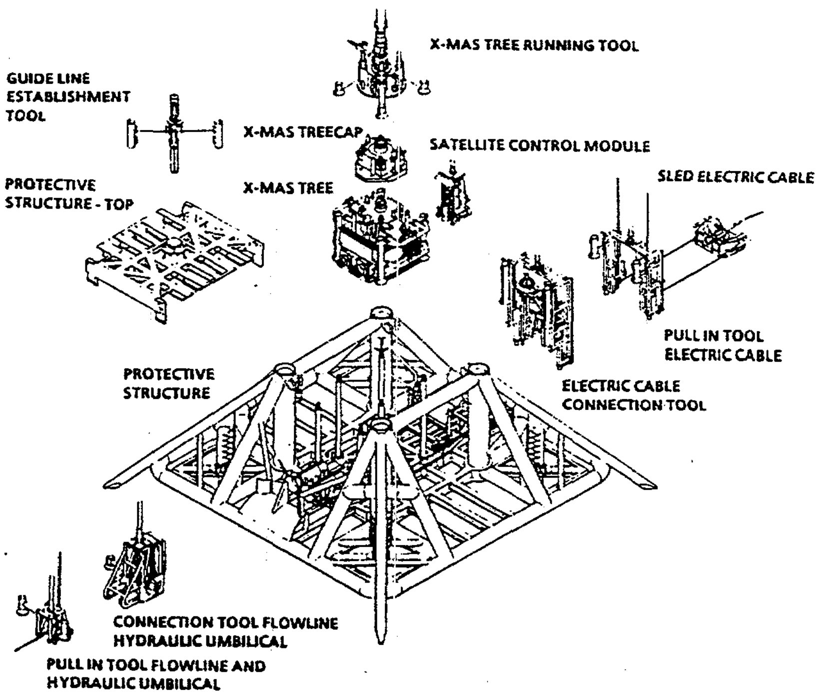


Figure 1.8 Satellite System

2) Repair:

Those systems which now been under operation for some years, repairment of the systems will be carried out, when problems due to corrosion, wear, connection loose or other kinds of damage occur. The repair operations can either be accomplished by divers in a smaller depth or by ROV and/or automatic machining system (underwater CNC system).

5. Other floating anchored systems:

One of floating anchored systems is the combined drilling and production semi-submersibles. They may be part of a subsea completion production setup. Before they are moved to new sites, these systems need to carry out underwater work before anchoring or maintenance.

Another type of platform is tension leg platform(TLP). Because the large working depth TLP has, this type of platform needs services from underwater vehicles during installation and a possible repairment.

1.2 Underwater systems and their functionality

Underwater tasks can be carried from the shallow water to very deep water (10- 10,000 m). Many different kinds of systems and techniques have been developed. These fallen into two categories: Manned or Unmanned system.

1.2.1 Manned Systems

Manned systems can be used as transport device, working equipment, tool carrier or just place for rest. They can be wet or dry systems depend on working depth and purpose. Table 1.2 is a list of manned submersible systems.

Table 1.2 The manned submersible Systems

Name	Working depth	Sea State
Diving air System	0 - 50 m	3
Diving saturation system	0 - 120 m	3
Wet manned vehicles	0 - 50 m	3
Manned submersibles	0 - 6000 m	6
Manned submersible with diver lock-out	0 - 120 m	3
Tethered one-man atmospheric suit	0 - 900 m	4
Tethered diving observation chambers	0 - 1000 m	4

1. Diving air System

This is a surface oriented technique of diving. It can be used for depths down to 50 m, and uses air as the breathing mixture.

In general, surface demand breathing equipment is used by commercial operators; the free-swimming, self-contained underwater breathing apparatus (SCUBA) can have advantages in shallow water.

2. Diving Bounce System

For deeper diving, a diving bell is used to transport the diver to and from the work site and provide a rest shelter and store for tools and equipment.

For short jobs or brief inspection work at depth greater than 50 m, it is convenient to use bounce diving from either a wet bell or a submersible diving chamber (SDC).

In the depth range 50-90 m, a wet bell of simple design can be used which holds two divers seated in the water, but with their head and shoulders in a dry hemispherical chamber.

At greater depths, 90-120 m, it is essential to use a closed diving bell or SDC. At the bottom, the divers breathe helix, a mixture of helium and oxygen, and they are supplied with heated water suits to combat the cold. Diving time normally does not exceed 1.5 h at 120 m.

For depths in excess of 120 m, the helix mixture is also used for decompression on completion of the dive. Bounce dives using helix are useful for short periods not exceeding 5 days.

3. Diving saturation system

This is a technique to obtain long duration dives at great depth. The diving system remains the same as bounce diving.

4. Wet manned vehicles

The wet manned vehicles are vehicles for diver use, mainly in shallow water no more than 50 m deep.

Such vehicle can reduce the total operation time and save the power of divers, since the vehicle will carry the divers to the site instead by swim to there by diver themselve. Wet submersibles have an advantage over dry manned submersibles for shallow water, because they require no pressure vessel. Wet manned vehicles have two types: that tows diver and has flooded cockpit.

5. Manned submersibles

Although underwater vehicles have been in existence for many years, it was used mainly for military purposes. The first upsurge of interest was in the 1950s and early 1960s when numerous small submersibles, known popularly as "minisubs" were constructed for oceanographic research. Unfortunately, they were extremely expensive to operate and maintain and had a poor reliability record with almost no commercial applications.

The first manned submersible to be used for commercial work in the North Sea was the former Vickers Oceanics' Pisces II which, was built primarily as a deep underwater observation vessel (operational depth, 730 m) with the ability to perform simple mechanical tasks using a hydraulically-operated manipulator having six degrees of freedom. This submersible was also equipped with a number of devices to increase its usefulness in underwater work

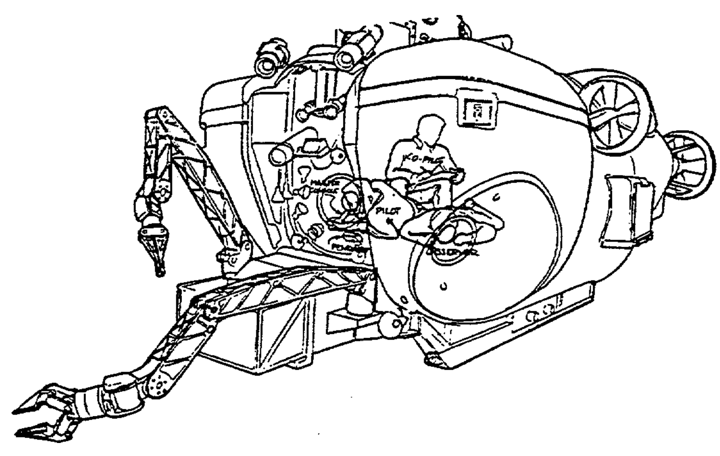


Figure 1.9 DSV-4 manned submersible

A number of manned submersibles equipped with powerful manipulators were constructed for the US navy for special tasks, such as retrieval Nuclear bombs lost in the sea, etc. Figure 1.9 shows DSV-4 manned submersible in working.

6. Manned submersible with diver lock-out

The Diver Lock-Out (DLO) submersible was introduction in the 1970s. The combination of a one atmosphere observation submersible with an associated diving bell or DLO provided the saturation diver with increased mobility.

The greatest single advantage of the DLO submersible is its ability to take the diver right up to the work site and provide him with visual supervision, lighting and power tools, etc.

7. Tethered one-man atmospheric suit

Owing to the complexities of deep-water saturation diving, many Diver Assistant Working Systems (DAWS) have evolved. One solution to this problem is the tethered one-man atmospheric suit or articulated diving suit. This type of equipment maintains the mobility and dexterity of the diver without the physiological problems of decompression by maintaining a normal atmosphere for the operator.

The one-man atmospheric suits consist of a rigid body and propeller; most of them also equipped with a master-slave mobilized manipulator. The materials to be used are cast magnesium alloy, fabricated aluminum, fiberglass, glass-reinforced plastic, etc. Some of them look like the human being with arms and legs, some of them more or less like an observation chamber with or without arm.

The one-man atmospheric suit can work in the cramped conditions of offshore structures to a depth of about 1000 m. Propulsion is provided the movement through 360° in the vertical plane. Power and communications are supplied through an armored umbilical, linking them to the surface. They are equipped with camera, lighting, tools needed for testing, maintenance, construction and salvage work. With depth capabilities of the units ranging from 450 m to almost 1000 m, the ADS is now a practical substitute for the ambient pressure diver and good backup system for ROV system.

The one-man atmospheric suit can accomplish the following underwater tasks.

1) platform inspection;
2) non-destructive testing;
3) platform maintenance;
4) drill rig support;
5) light construction;
6) seabed survey;
7) pipeline inspection;
8) salvage.

8. Tethered diving observation chambers

To overcome the restriction in electrical power available to free-swimming manned submersibles, several tethered diving observation chambers with limited maneuverability have been developed for operations offshore.

A manned Manipulation and Observation Bell (MOB), the MOB 1000 designed by Comex, is operated by two operators, with a capability of working down to a depth of 1000 m. The MOB is equipped with two manipulators, one for anchoring to underwater structures and the other with 6 degrees of freedom for working in front or below the bell and each of the MOB is equipped with a large amount of electronic and mechanical hardware to assist in underwater inspection and maintenance tasks, replacement of pingers and the recovery of equipment. A winch is also fitted to the MOB for lifting and handling loads.

1.2.2 Unmanned system

The family of unmanned systems has two main members, Remotely Operated Vehicle (ROV) and Autonomous Underwater Vehicle (AUV).

1.2.2.1 The remotely operated vehicle

The Remotely Operate Vehicle actually is one kind of remote operated robot that works underwater, is also a kind of submarine linked by cable or some other means to human operators. They perform tasks such as inspection or maintenance of offshore equipment or location of shipwrecks.

Integration of the technologies of robotics, artificial intelligence, and underwater vehicles has resulted in the emergence of a new field of underwater robotics.

Unmanned underwater vehicles can be classified into following categories. Table 1.3 illustrates working depth and sea state limitation of unmanned submersible system. We shall have a close look of them in the following sections.

Table 1.4 lists some of the ROVs commonly in use.

Table 1.3 Unmanned Submersible System

Name	Working Depth	Sea State
Observational/Documentation Unmanned Submersibles	0-6000 m	6
Observational/Manipulative Unmanned Submersibles	0-6000 m	6
Unmanned towed vehicles	0-6000 m	6
Tethered seabed vehicles	0-6000 m	6
Autonomous underwater vehicle	0-6000 m	6

Table 1.4 The list of ROV commonly used

Name	Manufacturer	Usage
MAX	UMI A.S	Inspection and Documentation
PLUTO	GAYMARINE S.R.L.	Inspection and Documentation
SOLO	Stolt Nilsen Seaway	Multi-purpose
SCORPIO	Ametek	Multi-purpose
SUPER SCORPIO	Ametek	Multi-purpose
TRITON	Perry Tritech	Multi-purpose

Name	Manufacturer	Usage
SEA HAWK	Stolt Nilsen Seaway	Inspection and Documentation
SEA OWL MK II	Sutec	Inspection and Documentation
SPRINT	Robertson Tritech	Inspection and Documentation
TRAPR	I.S.E	Multi-purpose
HYSUB ATP 10	I.S.E	Inspection and Documentation
HYSUB 25	I.S.E	Multi-purpose
HYSUB ATP 40	I.S.E	Multi-purpose
HYSUB ATP 50	I.S.E	Multi-purpose
HYSUB ATP 150	I.S.E	Multi-purpose
TROJAN		Multi-purpose
RCV 225	Hydro Product	Inspection and Documentation
DOLPHIN-3K	JIMSTEC	Multi-purpose
DOLPHIN-6K	JIMSTEC	Multi-purpose
EXAMINER	SubSea Dolphin as	Multi-purpose
PIONEER	Subsea Dolphin as	Multi-purpose

1.2.2.2 The Tethered Unmanned Submersible System

The Tethered Unmanned Submersible System is also called Remotely Operated Vehicle, ROV, which is more commonly used abbreviation in offshore industrial. Some people are prefer to call them underwater robot.

The main advantage of unmanned submersible over the manned version is that it is easily transportable and can be deployed either from vessel of. The unmanned submersible's other assets are that it is highly maneuverable, able to enter restricted spaces, with no working time limit, no danger to operation personnel. However, the opportunity for umbilical entanglement on a structure presents a risk and thus accurate underwater navigation systems are required. One method of reducing cable drag is to install the vehicle inside a cage lowered by an armored cable to the work site (Tether Management System, TMS), where the vehicle can emerge on a relatively short umbilical.

Two types of ROV are commonly used in offshore industry. The first is a small, light weight vehicle, specialized for observation and documentation; the second is a larger, heavier, more sophisticated multipurpose vehicle, may be equipped with manipulators, tools and instruments for inspection.

1. Observational/Documentation Unmanned Submersibles

These are small maneuverable vehicles fitted only with observational/documentation equipment, such as CCTV (Closed Circular TV), color still photography and cine. Vehicles of this type can be used in three specific applications:

1) visual inspection;
2) monitoring/diver assistance;
3) search/positioning.

RCV-225 (Figure 1.10) is a small, roughly spherical vehicle-nicknamed "the flying eyeball" that relays TV pictures to a control station. The vehicle is made by Hydro Products. It has numerous applications in the fields of underwater surveying and observation work

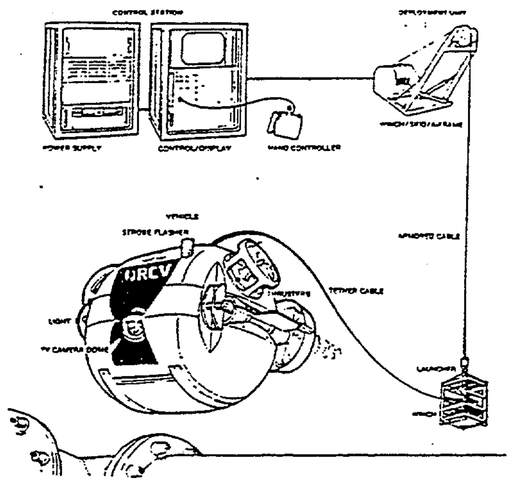


Figure 1.10 RCV-225 Documentation and inspection ROV

2. Observational/Manipulative Unmanned Submersibles

Numerous remotely controlled unmanned submersibles have been designed for various work tasks. Some of these are small limited work vehicles with a single manipulator; such devices can normally do no more that extend and open/rotate a claw. Other Submersibles in this category are sophisticated multipurpose work vehicles with two manipulators and specially designed instrumentation packages for underwater inspection and surveying.

DOLPHIN series ROVs (Figure 1.11) are constructed in Japan. These vehicles are mainly used to study the behavior of deep sea fish; and to conduct seabed survey. They move underwater by thrusters and receive commands via the umbilical link. They are equipped with manipulators; navigation devices; and TV and still cameras. The currently deepest operatable ROVs in the world are 6000 m class, a new 10000 m class ROV is under development in Japan.

TRITON, SCORPIO, etc., are among most common used multipurpose class ROV in North Sea. Typical ROV specification for multipurpose will be exhibited later in this chapter.

3. Unmanned towed vehicles

Deep-sea towed vehicles are used for hydrographic and seabed survey, and deep water fishery survey. They use combined side scan for sub-bottom profiling work. Several different towed vehicles have been designed for specific tasks in deep sea monitoring and seabed survey work.

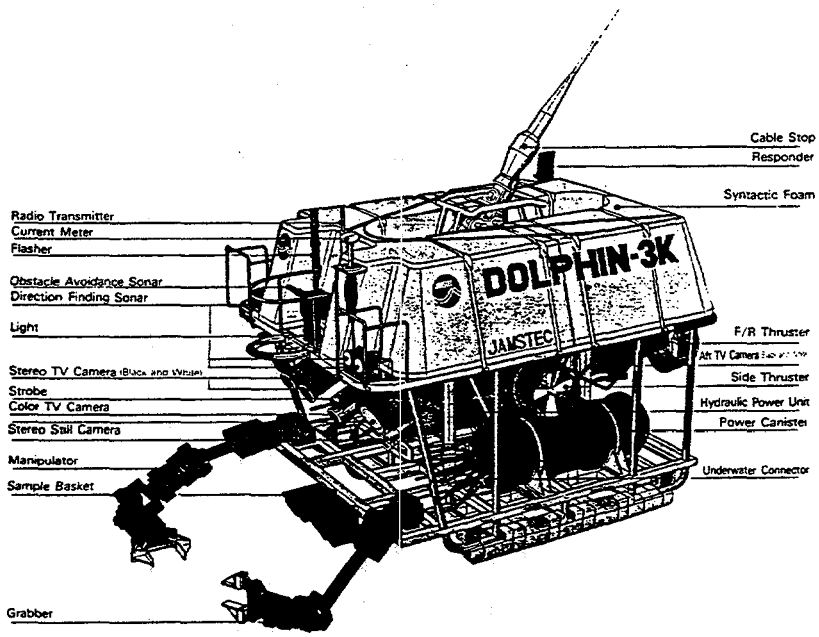


Figure 1.11 DOLPHIN-3K vehicle

With the prospect of deep-sea ocean mining, several towing systems have been designed for sea bed survey work down to 6000 m. The two most notable examples are the IBAK Deepsea Photo and TV Towing System, and the Hydro Products' Deep Sea Survey System. Both of these towed systems have a battery of CCTV cameras for observation and still cameras for record purposes. The IBAK deepsea system was designed primarily to allow systematic mapping of manganese nodule deposits on a large scale at a pre-fixed distance of 5 m from the seabed at a speed of 3 ms^{-1}. A low light TV camera is fitted as standard in conjunction with two still cameras, variable TV illumination, photo-strobe unit. All the cameras view forward and down, and an echosounder suspended from the towing cable of the IBAK system warns of dangerous obstacles further ahead, allowing the unit to be lifted clear.

4. Tethered seabed vehicles

Among other types of teleoperated devices that work underwater are remote controlled trenching equipment that automatically buries sub-sea pipeline in waters down to 500 m. These have been routinely used in the oil and gas field developments in the North Sea.

One such automatic trenching system was designed and built by Kværner Brug of Norway in the late 1970s. Two other companies, Brown & Root of the US and Volker Stevin of Holland, have joined this enterprise to form a new organization called KBV that has improved the hardware. The trenching system was used in 1983 to bury a 4 km length of pipe in the Brent field in the North Sea. Trenching is achieved with a mechanical suction cutter while another section of the machine grips a length of pipe and places it automatically in the newly-dug hollow. Now there are hundreds of companies are produce many kinds of ROVs that can perform different tasks with highly productivity.

For large-scale exploration of the seabed; the burying of cables and pipelines; the transportation of raw materials and other underwater survey and inspection tasks; there are considerable advantages in using unmanned submersibles that can be propelled two dimensional over the seabed. The main disadvantage of free-swimming submersibles is that they depend entirely on the reaction forces of water, and are mostly inadequate for developing the amount of driving force necessary for much of the work on the seabed.

1.2.2.3 The autonomous underwater vehicle

Autonomous underwater vehicle(AUV) is also called as Untethered Underwater Vehicle (UUV); marine or underwater robot. The tethered ROVs' operation range and space requirement were limited by the needs of tethers, so the untethered ROVs are developed. The first of them was made in 1963, but until 1979 the developing of the autonomous underwater vehicle starts to grow up rapidly, Table 1.5 shows some of the autonomous vehicles developed or under development.

Table 1.5 The developing history of Autonomous underwater vehicle

Year	Name	Usage	Depth(m)
1963	SPURV 1	Water measurement	6000
1972	UARS	Under ice mapping	457
1973	SPURV 2	Water measurement	6000
1975	SKAT	Ocean research	NA
1979	EAVE EAST	Test bed	914
1979	RUMIC	Mine counter measure	NA
1980	PINGUIN A1	Searching	200
1980	CSTV	Submarine control test	NA
1982	ROVER	Structure inspection	100
1982	ROBOT II	Bottom survey	91
1982	B - 1	Drag characteristic studies	90
1983	TELEMINE	Vessel destruction	150
1983	TM 308	Structure inspection	400
1983	AUSS	Searching	6000
1983	EPAULARD	Bottom Photography/Topography	6000
1984	ARCS	Under ice mapping	400
1986	ELIT	Structure inspection	1000
1987	LSV	Submarine test	NA
1988	XP - 21	Test bed	610
1988	MUST	Test bed	610
1988	SEA SQUIRT	Test bed	610
1988	RUV	krill research	250
1989	UUV (I)	Test bed	NA
1989	FSMNV	Mine neutralization	NA

Year	Name	Usage	Depth(m)
1990	UUV (II)	Test bed	NA
1991	AROV	Search and mapping	NA
1992	Mine Avoidance AUV	Mine counter measure	NA
1993	ARUS	Bottom survey	NA
1992	DOGGIE	Bottom/sub-bottom surveys	6000
1992	MOBATEL	Test bed	150
1992	DOLPHIN	Temp./Sal./Depth monitoring	6000
1993	Odyssey	Science Mission	6000
1993	FAU AUV	Science Mission	6000
1993	ARUS	Bottom Survey	NA
1995	CR01-A	Science Mission	6000

Untethered/autonomous submersibles are becoming a valuable tool in today's survey market and will used to perform the following tasks:

- under-ice survey
- search and identification
- bathymetric surveys
- bottom photography
- pipeline inspection
- nodule exploration
- underwater transportation

These tasks are only for early generation of the autonomous vehicle. Coming generations of autonomous vehicles will incorporate not only navigation; maneuvering; self-monitoring and obstacle avoidance, but also real-time video, imaging sonar and manipulators. Supervisory controlled Autonomous vehicles will become another fleet of the work vehicle of the tomorrow capable of supporting projects such as:

- Subsea production (installation, inspection and maintenance),
- exploratory drilling,
- pipeline repair,
- mooring systems,
- platforms (installation, inspection and maintenance, including cleaning)

The problems with acoustic sensors which caused by the air pumped under the hull, can be overcome by the radio controlled survey vehicle such as the Deep Ocean Logging Platform Instrument for Navigation (DOLPHIN), made by International Submarine Engineering, one of the world leaders in autonomous underwater machines. It is designed to run parallel line sounding at sea under moderately severe weather conditions. With a number of these running in front of the mother vessel, the time involved in bathymetric surveys could be dramatically reduced. Vehicles such as the diesel-driven type have an endurance of 12 knots.

Autonomous vehicles have taken a tactical approach in to the offshore industry by providing cost-effective alternatives to the survey industry. Over the next decade, the ROV manufacturers will aggressively examine the total range and potential of the autonomous vehicle and produce cost effective autonomous work vehicle systems to support the offshore industry.

1.2.2.4 Examples for Unmanned Submersibles

To give reader an idea of what typical configuration and specification of unmanned submersibles commonly used in offshore industrial, we compiled some detailed information about some vehicles.

1. Observational/Documentation ROV

The "Sea Hawk" is an advanced light work type ROV designed and built to Stolt-Nielsen Seaways specification. The vehicle is notable for its hydrodynamic faired shape and its exceptional maneuverability (Figure 1.12).

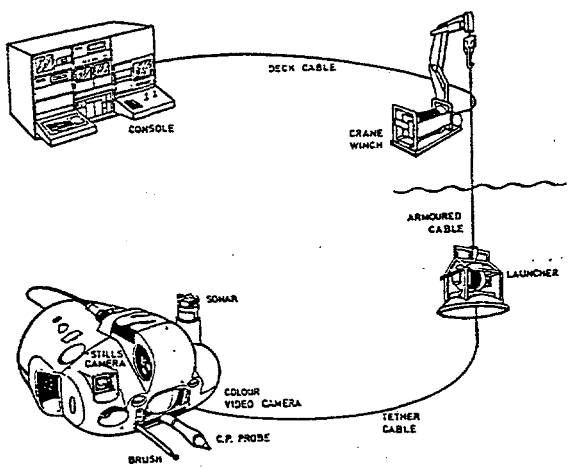


Figure 1.12 "Sea Hawk" Observation ROV system configuration

1) Standard configuration

System consists of:

- Sea Hawk vehicle
- Subsea launcher
- Crane/winch Unit
- Control console
- Control cabin/workshop

2) Standard equipment on board

The vehicle carries two color cameras; a rear view camera; color sonar; stills camera and choice of module. It contains a simple manipulator, or C.P. probe and wire brush or other tooling.

Table 1.6 Specification and configuration of "Sea Hawk"

Item	Description
Dimension: (L×W×H)	1.4m x 0.92m x 0.55m
Weight in air:	120 kg
Weight in water:	1 kg
Depth rating:	250m or 350m
Speed:	0-2.5 knots forward 0-1.5 knots reverse 0-1.5 knots lateral 0-1.0 knots vertical 0-20/sec rotational
Electrical:	380 or 440 VAC, 3 phases-30 kVA
Standard Equipment	Color video camera B/W video camera Mesotech 971 high resolution color sonar Magnetic compass rate gyro Canon 35mm SLR still camera 3 x 250 W variable lighting 7 x 0.3 kW thrusters Acoustic transponder
Optional Equipment	Simple manipulator C.P probe Cleaning brush Soft line cutter
Vehicle Control Features	Normal 3 dimensions by joysticks Auto/manual control in -Depth -Heading -Pitch -Roll -Altitude

2. Observational/Manipulative work class ROV

The TRITON ROV is one of the most used ROV in North Sea, and it is also one of the most versatile; multipurpose work and inspection ROV system on the market today (Figure 1.13).

TRITON ROVs can be used to performing heavy work tasks such as platform inspection and cleaning; pipeline inspection; drilling support; diver support; underwater remote intervention; telecommunications cable burial; and deep water salvage.

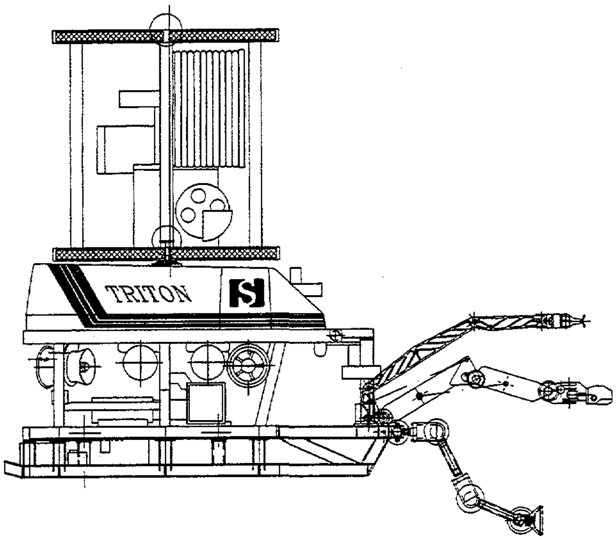


Figure 1.13 TRITON vehicle with TMS

The TRITON control system features automatic heading, pitch, roll, depth and altitude control, as well as operator adjustable control system gains which can be tuned to specific vehicle payloads; work packages; operating condition; and operator preferences.

1) Standard System Configuration:

- Standard TRITON ROV vehicle
- Pilot Control Console
- Electrical Power Distribution Unit
- High voltage Transformer Unit with interconnection cables
- TRITON 300 Class Tether Management System
- Standard TRITON umbilical
- Launch and Recovery System

2) Optional Equipment:

Spare I/O capacity is available in the standard TRITON ROV for cameras; pan & tilt units; sonar; altimeters, and other sensor packages. Spare hydraulic and electrical interfaces support a wide range at manipulators and tools such as cutters; grabbers; suction arms, etc. Optional computer I/O packages can interface to virtually any standard data gathering and analysis system.

The TRITON's 500 lb. reserve payload buoyancy supports a wide variety of custom work packages and special equipment installations.

Table 1.7 Specifications for TRITON ROV

Item	Components Specifications
Depth Capability	1,000m(3,300ft.) Available to 1,524m (5,000ft.) by changing flotation module
Maximum Speed (with 50 Hp HPU Unit)	Forward: (3 knots) Vertical: (1 knot) Lateral: (2 knots)
Turning Rate	40° per second minimum
Vehicle Dimensions	Height: 142 cm (56 inch) Width : 142 cm (56 inch) Length: 244 cm (96 inch)
Vehicle Weight in air	1,905 kg (4,200lbs.)
Payload	227 kg (500 lbs.) in addition to all standard equipment
Through Frame Lift Capability	2,045 kg (4,500 lbs.)
Propulsion System	2 eletro-hydraulic power units, each is 25 hydraulic horsepower, 2,400 VAC, 3 phases, 60 Hz, ~ 3,000 psi. 3 vertical thrusters at 180 lbs. thrust each, 3 horisontal thrusters at 450 lbs. thrust each. All thrusters motors are servo controlled.
Heading Control	Automatic ± 2 degrees or manual (park mode)
Pitch control	Automatic ± 2 degrees or manual maximum of ± 15 degrees.
Roll Control	Automatic ± 2 degrees or manual maximum of ± 10 degrees.
Depth Control	Automatic ± 15 cm (6 in.)
Altitude Control	Automatic ± 15 cm (6 in.) from 1-9 m (3-30ft.)
Power Source	2,400 VAC, 3 phases, 50/60 Hz supply to vehicle from surface power transformer unit 500 W, 115 VAC electrical power for work modules
Viewing System	One Merpro pan and tilt unit mounted in front of the vehicle. One Osprey OE 1311 black and white Four 250W ROS ultralites
Sonar	One UDI scanning sonar, Model AS360MSI
Manipulator	One Perry Hercules 5-function manipulator with 7-function valve package.
Emergency Pinger	O.R.E. Model 269, activated on loss of power.
Flasher	OAR Type SF50-1-100-PHOS
Auxiliary Equipment	One 1-atmosphere canister, 25 cm (10 in.) diameter with easily rnmovable head, contains vehicle spare electrical power and 40 capability; spare ports additional equipment are provided
Sensors	Heading - magnetically slaved gyro comp. Depth - one percent with 1% accuracy differential sensor for depth continous Pitch and Roll - 1% accuracy Altimeter - 1% accuracy.

3. Tethered seabed vehicles

Tethered seabed vehicles are mainly used in trenching work; some of them are also develped for underwater mining. The following is an example of a SeaBed Tractor (SBT) developed for AT&T for seabed cable burying.

The SBT (Figure 1.14) is a rugged compact unit designed for remote operation from a surface platform. It was designed to trench, inspect and repair undersea cables; umbilical systems and other subsea plant. While the SBT can operate in beach-zone and surf-zone conditions, it is ideally suited for working in the offshore area, particularly in confined and potentially difficult environments.

Table 1.8 The overall SBT vehicle and syssem specifications

Item	Components Specifications
Vehicle Dimension: (L×W×H)	8.8 m x 2.8 m x 3.0 m (with cutter)
Weight (Base Vehicle):	8 metric tons (air) 6.6 metric tons (water)
Weight (with Tools, Dry/Wet):	10.4/8.3 metric tons (with Cutter) 9.2/14 metric tons(with Jetter)
Payload:	4 metric tons
Speed (Base Vehicle):	0 to 6000 m/hr
Slope Crossing Ability:	30 degrees (ascent, descent, or side slope)
Tractive Force:	4 metric tons minimum continuous
Tracks:	Plastic track plates carded on steel running gear; debris protection, attachable grouser plates for slippery soil conditions
Track Drives:	Two "variable-flow" axial piston pumps driving direct Drive, track motors by individual closed- circuit, hydrostatic transmission with internal oil cooling provided, independent proportional control of swash plates permits infinitely variable and differential speeds.
Turing Radius:	Less than 10 meters
Operating Water Depth:	0 to 1400 meters
Track Drive Power:	Total 220 kW, Electric motor driving dual variable displacement hydraulic pumps
Crane/Grab:	4 functions, 3 metric ton - meter minimum capacity crane with 3 function cable grab; 5.0 meter track; to full 360 degree coverage
Vehicle Sensors:	Acoustic navigation system, cable entry angle, submerged depth, altitude, pitch and roll. distance traveled, cable length counter, speed, moisture levels, hydraulic system pressure. position sensors, umbilical and telephone, cable tensions, tool linkage position and lends, crane position and loads, hydraulic oil volume, bellmouth positions (open/close, repeater detect, and percent tilt), cable-in-share proximity detection, temperature.

Item	Components Specifications
Surveillance:	Search and obstacle avoidance sonar, magnetic cable locating and tracking system, 4 monochrome SIT video cameras. 1 high-resolution color video camera, pan-and-tilt units with position feedback, lights, hydrophone responder with transponder capability, altimeter
Manipulator:	Seven-function Schilling manipulator with tool rack holding cable cutter, pinger modules and cable gripper tool
Trenching System:	Three identical electric motors driven pumps feed a common manifold. Individually controlled valves permit jet nozzle configuration, thruster operation, and operation of the soil eductor.
Soil Capability:	Up to (100 kPa) hand clay with Jetter Up to (400 kPa) rock with Rock wheel Cutter
Trench Depth:	1 meter in single pass with tool engaged
Trenching Speed:	50 to 1000 m/hr
Thrusters:	Four 1" diameter thruster nozzles for controlling heading during deployment and recovery.
Ship Handling Equipment:	rated to 14 metric tons SWL
Winch Recovery Rate:	30 m/min maximum

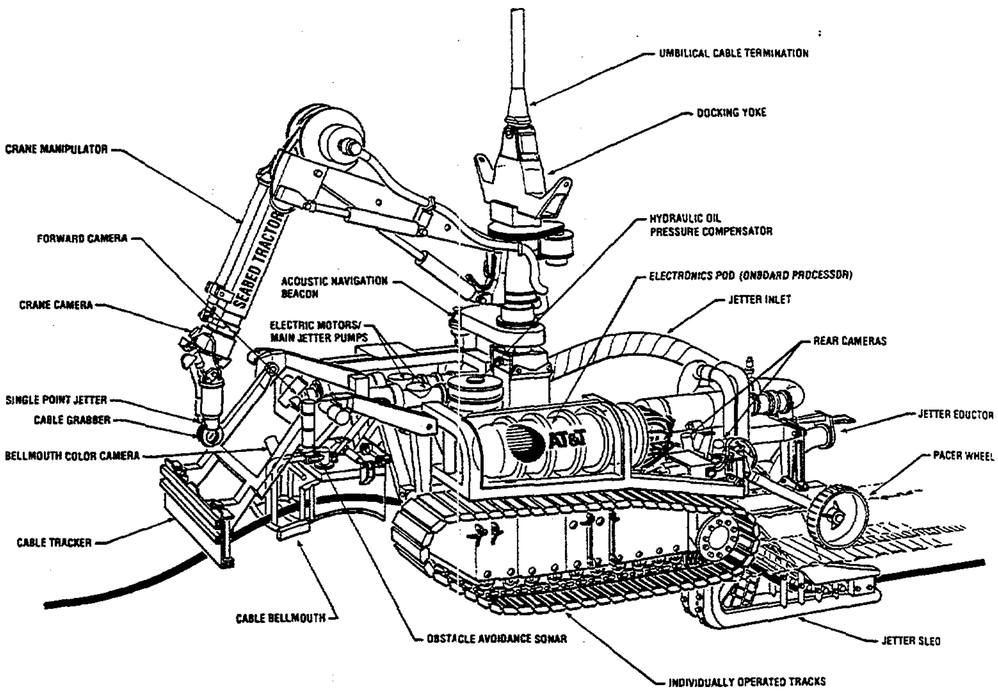


Figure 1.14 AT&T SBT Sea bed tractor

1.2.3 ROV sub-systems and main functions

The ROV consists with the following subsystems:

- ROV/Launcher handling
- Launcher construction
- ROV main construction
- Umbilical/tether cable and Umbilical/tether handling system
- Propulsion system
- Manipulation system

(1) ROV/Launcher handling

This system is used for handling of the ROV or the Launcher from the support station into the water, releasing the ROV from the hoisting wire or from the launcher, and the reversed operation.

The handling operation is normally done by A-frame over the stern of support vessels, through moonpool or frequently over the side by using A-frame; hydraulic crane or a derrick.

Normally there is a damping system to reduce the pendulum motions during the complete water to deck transition.

Most ROVs which without launcher (normally small ones) are handled by a separate hoisting line, not by umbilical. Release and connecting to the hoisting line are normally carried out in the surface close to the support station. A diver assistance from a small boat is often needed for connecting.

For the systems with launcher, the ROV is attached to the launcher during handling. Normally a steel armored umbilical, also acting as hoisting line, is used between the surface control and the launcher. The launcher normally is also a Tether Management System(TMS).

Release and connecting of the ROV are usually executed remotely at the ROV's working depth.

Figure 1.12 and Figure 1.15 show the two different launcher configurations that are commonly used.

(2) Launcher construction

The launcher is normally designed like a cage, with the ROV clamped to it. The ROV can be fully protected by the structure of launcher.

The mechanical locking mechanism is usually used to release the ROV by remote control and locking the ROV automatically when it comes back into the correct position.

The launcher is handled by a strong umbilical, often with two contrahelically wound steel armors layers, and containing the tether-cable to the ROV on a slipringless winch.

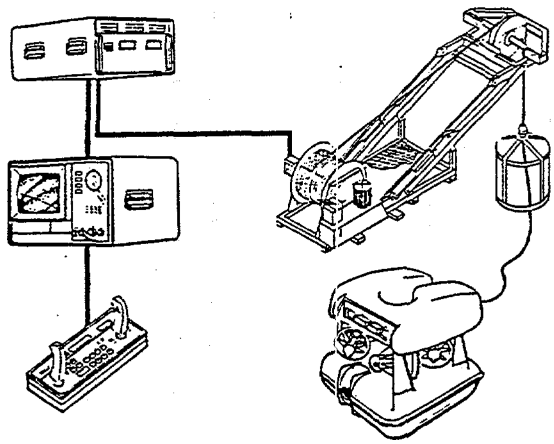


Figure 1.15 A-frame launcher for SPRINT

(3) ROV main construction

The main construction of ROV is used to protect all sub systems and components with ROV during operation. It is include outer structure and the buoyancy system.

Most of the medium and large size ROVs use rectangular open framework, of either steel or aluminum. All components are enclosed within the framework. The buoyancy system is attached to the top of the framework to provide neutral buoyancy and roll/pitch stability. Some of the ROVs are designed as modules, so they can be assembled for different purpose.

Most of the small ROVs are shaped like spheroids or a pressure resistant hull. The buoyancy material normally is put inside the ROV frame, but one can also find design with buoyancy material outside the frame. Except the thrusters, other components are contained within the structure. They have a considerable lower drag profile in front than any other directions.

The main construction and working configuration of a typical modulated ROV such as AROWS JCV is exhibited in Figure 1.16.

(4) Umbilical/tether cable and Umbilical/tether handling system

The umbilical ROVs have their own requirement to the umbilical and tether cable. There is also a system which is special used to handling the umbilical or tether, which is normally called TMS (Tether Management System).

The umbilical or tether cable consists a group of power conductors for power transmission, and a group of coaxial cables; twisted pairs or optic-fibre lines for signal transmission. It is also constructed with water blocking jackets; kevlar stress member and grounding copper braid.

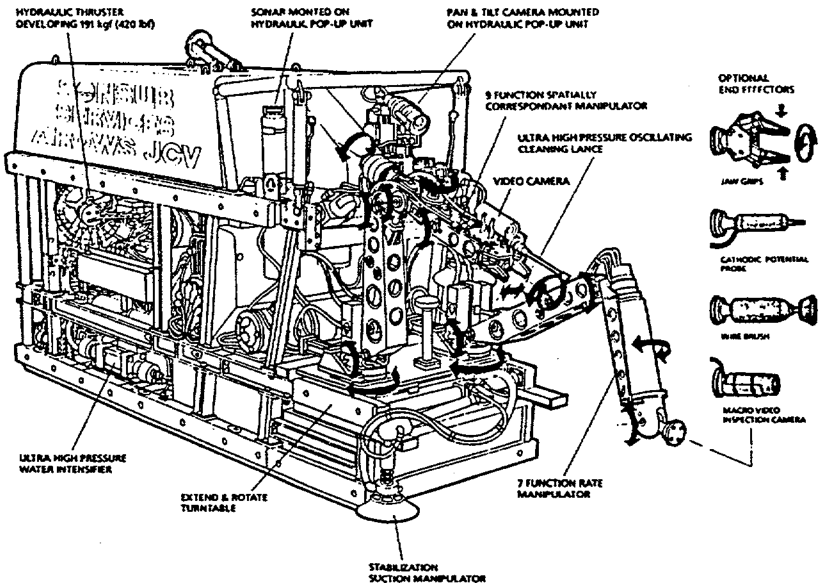


Figure 1.16 The main construction and configuration of AROWS JCV

There are several options for the umbilical/tether handling. In one option is the umbilical handled directly by a winch on the support station. This configuration sometimes causes problem, because of the umbilical is possible to be cut by support vessel's propellers. When the ROV is hoisted by the umbilical, it is seems safer.

If the umbilical is continuous from support station to ROV, the length of it is normally from 500 m to 1000 m, but they are usually not designed for ROV hoisting.

Another is use armored umbilical for launcher handling from a crane or winch which installed on the support vessel. The tether cable is handled by a remote controlled winch (TMS) from launcher to the ROV. There are some ROVs with integrated tether winch. Normally the tether cable handled by launcher is easier and safer for the cable, but the control of the winch is more difficult.

(5) Propulsion system

The ROV propulsion system includes thrusters and motors, sometimes water jets.

The thruster motors include: Hydraulic motors, electric motor with or without brushes, driven by DC or AC.

For electrical motor, thrust regulation is provided by varying the varying the motor's number of revolution or by controlling the pitch of the propellers while the electric motor is rotating at constant speed. The problem for electric motor is lower output to weight and volume ratio, and the reliability is also lower than the system which uses hydraulic motors.

Hydraulic motors are powered by an electro-hydraulic aggregate on the ROV. Thrust regulation by servo valve control of motor revolutions. The hydraulic motor is more compact and efficient. The problem for this system is the high frequency acoustic noise, which will influence the sonar and the acoustic navigation systems, and because of the poor overall efficiency.

Water jet system is another alternative. It is propellerless, normally driven by an electrically powered submersible pump. Thrust regulation by throttle valves and nozzle selection. This configuration is seldom used, because of the low efficiency, but it is sometimes more compact and reliable for a small system.

The design of the propulsion system is important for ROVs, since this determines the maneuverability. Several configurations for the thruster arrangement have been developed:

- Triangular configuration is the three thrusters forming an equilateral triangle with center of the ROV. It is very good for structure inspection because of the maneuverability and the ability of withstand currents from any direction. This configuration is most suitable for small ROV.
- The configuration with forward thrust with vertical thrusters provides more freedom degrees. This is usually good for general purpose tasks, such as pipeline inspection and construction inspection. This configuration is suitable for bigger ROVs, but the attainable pitch and roll angles may be limited.

(6) Manipulators

The manipulators are the acting system for collecting sample, handling tools, operating instruments and achieving other requirements.

The manipulators often have 3 to 6 degrees of freedom, are of joint type and generally are driven by hydraulic cylinders. Detailed information about manipulator will be introduced in section 1.3.

(7) Stationkeeping equipment

When the ROV executes some operation, for example the surface treatment, valve replacement and repair, normally there is force occurs, so it is very important to remain the ROV stable and the position unchanged.

There are several equipments can be used in such operation, such as suction pads; claws and stabs.

Suction pads uses hydrostatic attachment, normally hydraulic driven. Some of them are mounted on simple manipulators (sticky feet). They have reasonable holding forces at rather small size and light weight, but the power consumption is rather high. The holding force is very dependent of the roughness of the surface. Sometimes their thin and weak rubber structures are also easy to be damaged.

The hydraulic operated claws (normally installed on a simple manipulator) can supply very firm attachment of the ROV to a steel jacket. The problem of large size made that it occupies too much space on ROV; sometimes it is also difficult to find a proper or close enough place for claw to handle.

The stabs are also used to fix the ROV to a pre-designed structure. It forms a V-shaped or cup shaped stab which mounted on the ROV to press against a platform leg or ROV panel. This kind of ROV stationkeeping is normally designed for one part of a structure. The problem of this is the ability to withstand reaction forces; it is limited to the propulsion force and has to be used on specially designed structures.

(8) Tools and sensoring devices

The tools and sensoring devices are used to perform some particular inspection, repair or replacement operations. They include:

- Tools to remove debris.
- Tools to remove marine growth and clean the surface.
- Tools for surface treatment, both for concrete and for steel structure.
- Instruments for metric measurements.
- Sensors to measure depth of pipe burial.
- Sensors to measure length of pipeline free spans.
- Instrument for straight-line measurements.
- Instrument for cathodic protection measurement.
- Instrument for material thickness measurements.
- Instrument for crack detection.
- Instrument for leak detection.
- Cameras and lights
- Equipment for valve replacement.
- Equipment for welding operation.
- Equipment for pipeline cutting.
- Equipment for pipe connecting.

1.3 Underwater manipulator

One of the major complexities of the underwater vehicle systems lies in the manipulative systems of the vehicle. Those manipulator arms which use push buttons, joystick controllers, master-slave controllers, are quite complex and require a proficient operator. The recent progresses are in the feedback master-slave arm control, and the supervisor control. To incorporate the hydrodynamics in the dynamic model and apply artificial intelligence concepts to develop a smart supervisory system for underwater manipulator are also get positive results.

In manipulator construction, modern drives including electric drives with optimized design and new materials are used. Also, advanced non-linear controllers are being developed to undertake complicated tasks such as inspection, welding, replacing valves.

1.3.1 Example of typical underwater manipulator

The Schilling TITAN 7F is one of the most common underwater manipulators used in North Sea It is 7 function and with force reflex close loop control. It is not only widely used in underwater operations but also used in "in air" teleoperations. Its specification is listed in Table 1.9. The structure and working envelop are exhibited in Figure 1.17 and Figure 1.18

1. Mechanical Assemblies

The mechanical assemblies that constitute the slave arm structure provide a skeleton for the hydraulic actuators which effect arm movements. The skeleton is comprised of four major components.

- Base Segment
- Upper Arm Segment
- Forearm Segment
- Wrist Assembly

2. Structure and construction, the component commonality

Each arm segment is made from titanium plate which is cut and milled to dimension to form a pocketed, shear-web structure and then electron-beam welded to create each complete arm segment. This construction technique produces a lightweight; extremely strong; torsionally rigid and corrosion-proof structural assemble. In sensitive areas, the electrochemical action is prevented by oversized bearings combined with composite bushings and sleeves.

The TITAN 7F Manipulator is symmetrical about the vertical, so operation on either the right or left side of the vehicle does not require any hardware change.

Many components of the TITAN 7F Manipulator are identical, major common components include:

- All servovalves throughout the manipulator are identical and interchangeable.
- The shoulder and elbow pitch linear actuators are identical and interchangeable.
- Critical internal components of the wrist pitch and yaw rotary actuators are identical and interchangeable.

- Wrist pitch and yaw rotary actuators and waist azimuth rotary actuator utilize identical seal sets.
- Bearings used in the shoulder pitch and elbow pitch are identical and interchangeable

Table 1.9 Schilling TITAN 7F manipulator technical data

Item	Components Specification	Speed
Degree of freedom	7 servo functions (6+claw open/close)	
Maximum reach	1.98 m (78 inches)	
Lift capacity at full extension	1112 N (250 lbf)	
Wrist Yaw	180°	400°/sec
Wrist Pitch	180°	400°/sec
Shoulder Pitch	90°	90°/sec
Elbow Pitch	120°	90°/sec
Wrist Rotate	Slaved 270° or Continuous rotate	0 - 90 rpm
Waist (Forearm) Yaw	270°	90°/sec
Wrist torque	110 ft lbs (Standard)	
Claw grip opening	203,20 mm(8 in)	
Claw grip force	1556.8 N (350 lbs)	
Weight (in air)	62.9 Kg (138.5 lbs)	
Weight (in sea water)	106.5 lbf	
Weight of master arm	5.9 Kg (13 lb)	
Materials	6-4 titanium	
Oil pressure	204 Bar(3000 psi)	
Flow rate	2 gpm	
Working depth		
Pressure positive compensation	Yes	
Electrical supply (In seawater)	12, 24, 20 VDC, 12 Watt	
Electrical supply (Surface)	110-230 VAC, 60 Hz, 12 Watt	
Data link requirements	Single twisted wire pair	

3. The control functions

- Dynamics: Select different mode in dry or wet environment
- Wrist mode: Select servo position of the rotation or continues rotate
- Freeze : Freezing all the functions on the current position
- Transparent reindexing : Reindexing the current with the master arm when unfrozen.
- Jaw Mode: Select the open, toggle or freeze mode
- Range of motion limits: To limit the range of motion of each function to protect the manipulator or the structure.
- Stow/teach: Return the slave arm to a pre-determined stow position, and can teach the slave arm to a new stow position or in a new sequence. The data are stored in an EPROM.
- Diagnostics: To evaluate master, slave and commanded position values for joint positions.

- Robotics: Allow the user use an external device to store and retrieve standard routines.

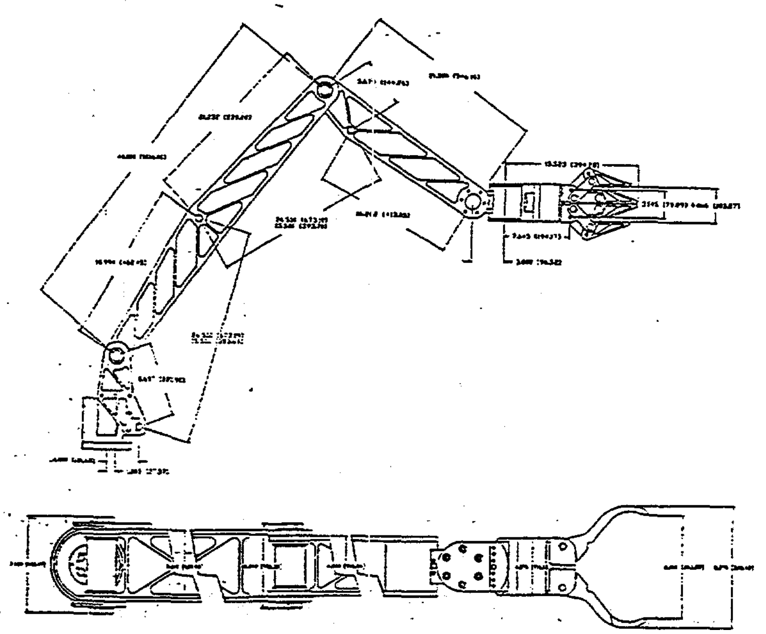


Figure 1.17 The structure of TITAN 7F manipulator system

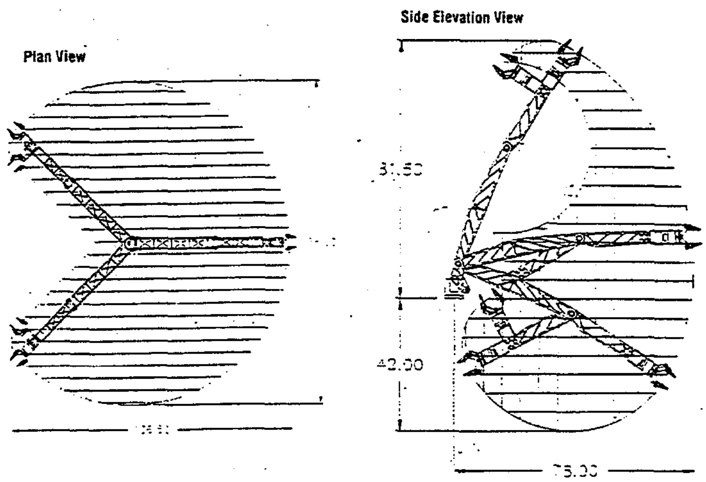


Figure 1.18 The Envelop of TITAN 7F manipulator system

1.4 Tie-in System

This operation is one of the most important operations during the installation phase of subsea production system. It consists of pull-in and connection both rigid pipelines and flexible flow lines.

Tie-in operation for the pipeline or umbilicals includes pickup the end of pipe (termination on the pipe or umbilicals) previous laid by lay vessel, the pull the pipeline or umbilicals towards the fixed termination. After both terminations pulled together, the connection system starts to connect them together by mechanical clamp or welding.

The detailed procedures and system of tie-in operations will be discussed in Chapter 5.

There are basically two different concepts in respect to different connection methods.

- Mechanical clamp connection
- Hyperbaric welding connection

These two types of connection tools nowadays are normally remotely control and diverless operated. Some of welding operations are carried out by the help of human welder in small water depth.

Two types of equipment for connecting of pipelines by applying these two methods have been developed.

The equipments using mechanical clamp connection concept are represented by Kværner's pull-in tool, connection tools used in TOGI and Tordis project and combined pull-in and connection tool which is used in TROLL OLJE project.

The equipment using Hyperbaric welding connection concept is represented by Stolt Comex Seaway a.s by using of TIG (TIG = Tungsten inert gas) hyperbaric welding, and they are also considering to develop a new equipment which is called THOR 2 (THOR = Tig Hyperbaric Orbital Robot).

1.5 Miscellaneous underwater working systems

1.5.1 ROT system

ROT system is commonly used during the installation; completion and operation phase of an oil field. Reliable ROV intervention systems will be of vital importance to the overall success of the project.

The TOGI ROV Tooling System (Figure 1.19) is developed to use standard ROV to perform tasks such as guideline installation and retrieval, wire cutting, observation and debris cleaning. For the Subsea Station, a tooling system has been developed to perform the various specialized tasks. The ROT will operate primary and secondary valve functions throughout the lifetime of the Station. In addition to the mechanical overrides on X-mas tree/running tool valves, isolation valves on the Template Manifold and Pig Module, the ROV will operate hotline stab-in functions for the hydraulic override on connectors. Injection of grease and dehydration fluid will be accomplished by a combination of ROV docking and manipulator tool operation. Technical data please refer to Table 1.10 and Table 1.11.

The total number of valves with interfaces for the operation/override by the ROV system is approximately 220, ranging in size from 1/4 to 20 inch.

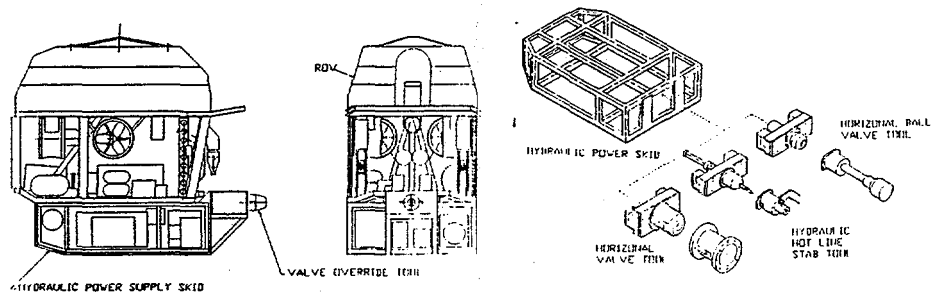


Figure 1.19 The structure and tool configuration of TOGI RGT

Table 1.10 Technical data of TOGI tooling system

Dimensions (Overall)	
Length	1975 mm
Width	1170 mm
Height	471 mm
Weight (with skid mounted tool, full comp system and reservoir)	505 kg (in air) 1.5 kg negative buoyant (in water)

Table 1.11 Performance Data of TOGI tooling system

Performance Data	
Supply Pressure (ROV)	3000 psi
Supply Flow (ROV)	28 LPM (max)
Output Pressure	2800 psi
Output Flow	5 LPM per Valve (max)
Usable Reservoir Volume	40 L
Operating depth	350 m
Hydraulic Fluid Medium	Castrol Brayco Micronic 864
Skid Power	110 VAC
Console Power	110 VAC
Telemetry Link Material	Shielded Twisted Pair

1.5.2 Specialized underwater working systems

Now, many underwater tasks are accomplished by divers and ROVs. There are also many different kinds of specialized underwater working systems are under developing, such as Inspection Robot, Scimitar Cleaning Vehicle, Figure 1.20 and Figure 1.21 are the conception drawings of them.

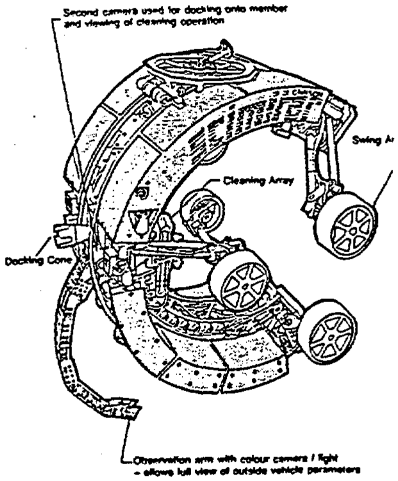


Figure 1.20 SCIMTAR-remote underwater fouling removal device

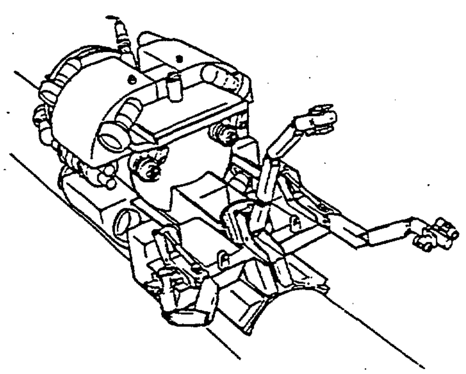


Figure 1.21 Inspection Robot

2 Control system for underwater equipment

2.1 Underwater Control system

This section provides definitions and theoretical foundation of the elements implemented in an underwater control system. The following sections provide basic functional requirement and current practices in the design of control systems; control elements; sensors and data acquisition system; chosen of control lines and some consideration of control fluids are also mentioned. A range of currently used control system examples are presented with the important operating features of them.

As we know, an underwater equipment is an equipment or device which locates distance from the human operator, and normally requires human interactive with them. These systems are normally defined as a remote control system.

In a remotely operated system, two main parts are involved, they are:

Host: The system that gives the primary instruction, it can be a person or/with a computer.

Remote: The system that receives the instruction from the host and takes action according to the instruction. It normally consists of a control system for decode and distribute the control, and having the actuators to take action.

The host end consists a surface control station or portable console, signal transmission device and power supply. This end is normally well protected.

The remote end contains single demodulating device, power conversion system, sensors and actuators. Some part of system is exposed in water and pressure, and some other part is closed in a canister to protect the equipment against pressure, moisture and any other unfavorable conditions.

2.2 Control system, General

In this section, we discuss alternative underwater control systems and the requirements demanded for each alternative..

2.2.1 Major control categories of underwater equipment

Consider the method of powering the system and the way of controlling the system. We can classify the control systems as a matrix in Table 2.1 or list as follow:

1. Classified by the method of control
   - Directly control
   - Programmed/sequence control
   - Autonomous control
   - Supervisor control

2. Classified by the location and type of signal

- Hydraulic signal from surface, discrete control
- Electric signal from surface, discrete control
- Acoustic signal from surface, discrete control
- Hydraulic signal from surface, sequence control
- Electric signal from surface, sequence control
- Acoustic signal from surface, sequence control

Table 2.1 Matrix of Classification by Power source

Power source	Actuator Type					
	Manual	Feedback	Hydraulic	Feedback	Electric	Feedback
Powered by man	✓	✓				
Surface Hydraulic			✓	×		
Subsea Hydraulic			✓	×		
Surface Electric			✓	✓	×	✓
Subsea Electric			✓	✓	×	✓

3. Classified by powering the system

The control systems can also be classified by the power source of the system, it can be represented by a matrix as Table 2.2 or a list as follows:

- Powered by operator
- Direct hydraulic from surface, hydraulic to the actuator
- Direct electricity from surface, hydraulic to the actuator
- Direct electricity from surface, electricity to the actuator
- Hydraulic supply from other system subsea, hydraulic to the actuator
- Electricity supply from other system subsea, hydraulic to the actuator
- Electricity supply from internal power subsea, hydraulic to the actuator
- Electricity supply from internal power subsea, electricity to the actuator

Table 2.2 Combination of signal and power location

Signal		Manual		Hydraulic		Electric		Acoustic	
Power		S	L	S	L	S	L	S	L
Manual	S								
	L		✓						
Hydraulic	S		✓	✓		✓		✓	
	L		✓	✓		✓		✓	
Electric	S		✓	✓		✓	✓	✓	
	L		✓			✓		✓	
Acoustic	S								
	L								

S - Surface, L - Local (Subsea)

Any manned underwater equipment is under direct control of the operator. From the description in chapter one we can find out that, at shallow water or under a special diving condition, the underwater equipment is power directly by the operator or assisted by power from surface. The directly powered systems are powered by the operator through a direct mechanical connection, either metal cables, tapes, or rods. The separation distance of the remote unit from the operator was limited, as well the speeds and forces of operation. The operator directly supplied and controlled the power to the various degrees of freedom. An advantage of the direct drive was the direct-force feedback to the operator.

Externally powered underwater equipment uses electric and/or hydraulic to drive the system. It allows the operator to work at a distance from the work site, but it also carries up some new problems. The operator now outputs signals to a control system that modulates the power to the remote unit. The power that the operator must provide is greatly reduced, but operator's feeling ability is also diminished by the indirectly operate, so the operation becomes slow and imprecise, unless the forces, position and the other information can be reconstructed in a form that the operator can be accepted.

2.2.2 Type of control system

Control systems may be classified by their principle of logic design and methods of communication. Figure 2.1 classifies the control system by its control logic principle.

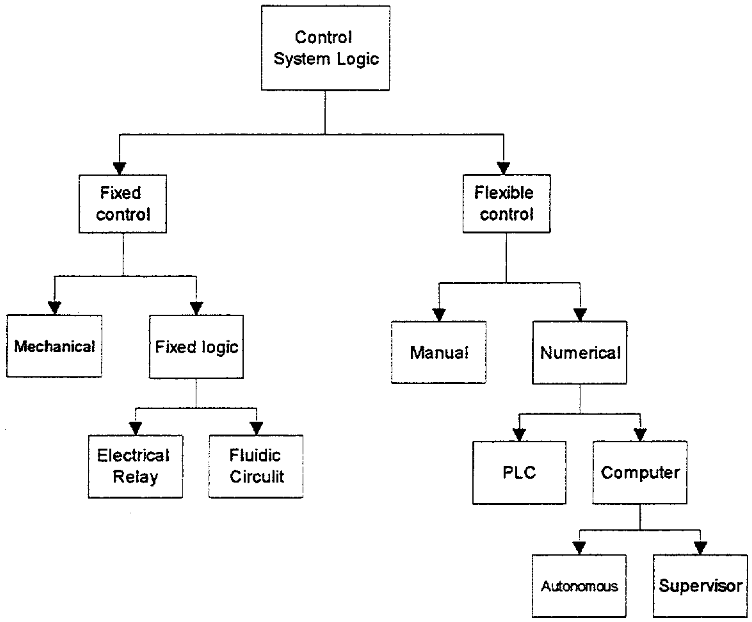


Figure 2.1 Classify control system by control method

1. Fixed Control System

The fixed control systems are dedicated to specific tasks to control fixed sequences of events. This category is in turn classified into:

1) Mechanical Control System

A mechanical control system is a mechanical mechanism built on a combination of mechanical components such as cams, gears, etc., to apply pure mechanical control to the physical unit concerned.

2) Fixed Logical Control System

This is made of logic circuits, which are based on Boolean algebra. These can be realized by fluidic circuits or electric ones.

Pneumatic or hydraulic valves are used to implement the common logic functions such as AND, OR, NOT, etc. Hydraulic systems are used when high power is required, the pneumatic ones are used with lower operating power. Electrical logic circuits are simple wired circuits, or even more sophisticated programs stored in Read-Only-Memory (ROM) or in Programmable-Read-Only-Memory (PROM).

2. Flexible Control System

Flexible control system, such as programmable control system, achieves the flexibility by tob be programmed to adapt to new task. Under this category are all the computing systems, Programmable Logical Controllers (PLC), Computerized Numerical Controllers (CNC), etc.

The programmable control system issues control commands and data as a result of the executions of the control programs. To apply the required control to the concerned physical unit, control can be performed with (closed loop control) or without feedback (open loop control).

The interface devices are located between the programmable control systems and the physical devices, and between the different interconnected programmable control systems to smooth out the differences in timing, data formatting, etc. Figure 2.2shows a schematic drawing of an interface device between a programmable control system and a physical device. The main elements of the programmable control unit are: a memory to accommodate programs and data; a Central Processing Unit (CPU) to execute control programs; and an Input/Output (I/O) unit.

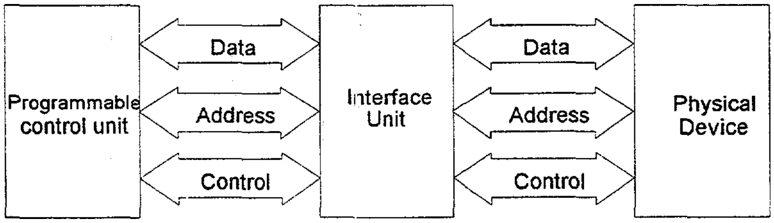


Figure 2.2 Interface device between Programmable control system and physical device

2.2.3 Objects to be controlled

The main objects to be controlled by underwater control system are different type of actuators, and sensors for information gathering. Actuators used by underwater equipment are hydraulic cylinder (linear and rotational), hydraulic motor, AC or DC electrical motor.

The control of actuators can be speed control and direction control, for example, speed of motor and cylinder, rotational and linear direction of them.

Figure 2.3 shows some of the actuator's functional control.

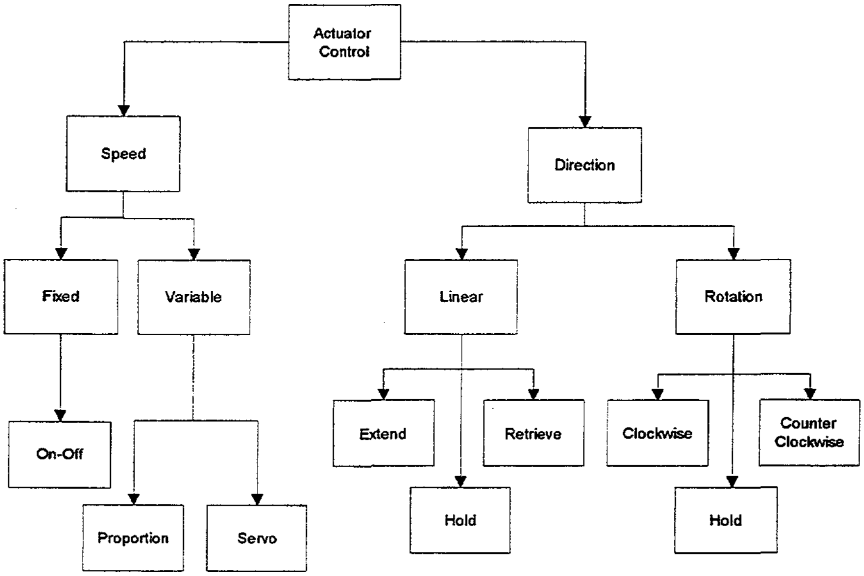


Figure 2.3 Actuator function control

2.2.4 General control considerations

Control of flexible underwater working system requires the coordinated control of several degrees of freedom while observing a multitude of kinematic, dynamic, and environmental constraints. To follow the specifics of a given task, different sensor signals must be interpreted in real time. Manipulation tasks can often be performed in different ways, consequently manipulator arm control implies a multilevel decision and monitoring process at both the information feedback and control input channels of the controller.

The human operator is a key control element in all of the applications of underwater working systems and in all (manual and/or automatic) control modes (Figure 2.4 shows the control concept of the teleoperator). It is the human presence in the control that provides a versatile response capability to the remotely operated manipulator in highly variable or unpredictable situations. The human's functional role is bi-directional: the operator receives information from the remotely operated system and sends control commands to it. The operator's manual skill and perceptive, cognitive, and decision making abilities are important determining factors in the overall task performance.

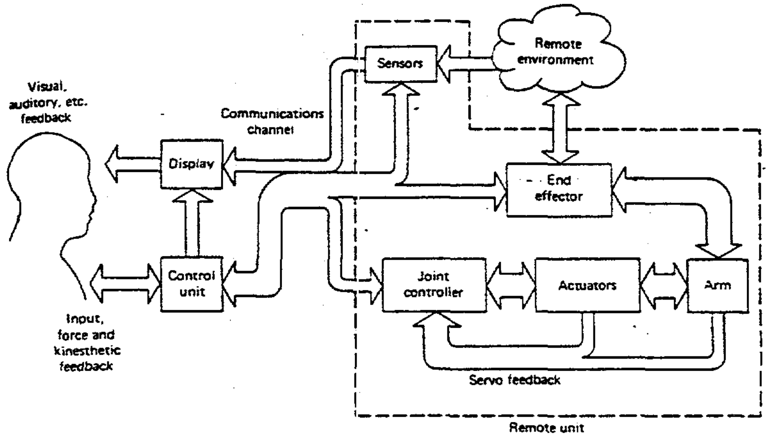


Figure 2.4 The conceptual diagram of teleoperation from the operator center of view

It is recognized that the human operator's input and output channel capacities are limited. In this sense, the human operator represents a limiting factor in the information and control environment of a remotely operated manipulator. For example, the operator's information processing capacity can be easily overloaded. Additionally, the human input and output channel capacities are not only limited but also asymmetric: The human has much more information receiving(input) channels than information conveying (control output) channels.

Following an operator centered view, the general objectives of control, information, and man-machine interface development for advanced teleoperators are:

(1) Development of devices and techniques that enable the operator to convey control commands to the remote manipulator in comprehensive and task-related terms.

(2) Development of devices and techniques that condense and display the control information in terms and formats compatible to human perception and attention allocation in the environment of a control station designed for remote manipulator arm control.

The control and information paths between task description and task execution in remote manipulation pass through several major functional transformation blocks. The main functional elements of a multilevel manipulator control/information organization can be summarized as Figure 2.5. The first or bottom level is embedded in the time continuum and environment, all the sensor signals are generated at this level. This level output the greatest amount of information and involves both the control and processing of continuous variables. The second level can be called the algorithmic level. At this second level, control and information variables are handled by a finite number of computer algorithms, and messages are transmitted to the lower and higher levels of a finite number of time instants.

Transformation of the operator's task description both to actuator reference commands and to control context of sensor data are generated by computer algorithms at this second control level. The third and highest control level is the human operator. In the context, the main function of the human operator is task description and "supervisory" monitoring of task execution. The operator selects, quantifies, or modifies the algorithms for the lower control levels. Of course, this highest control level is based on the human attributes of thinking, learning, judging, and setting "goals" for a machine with known characteristics.

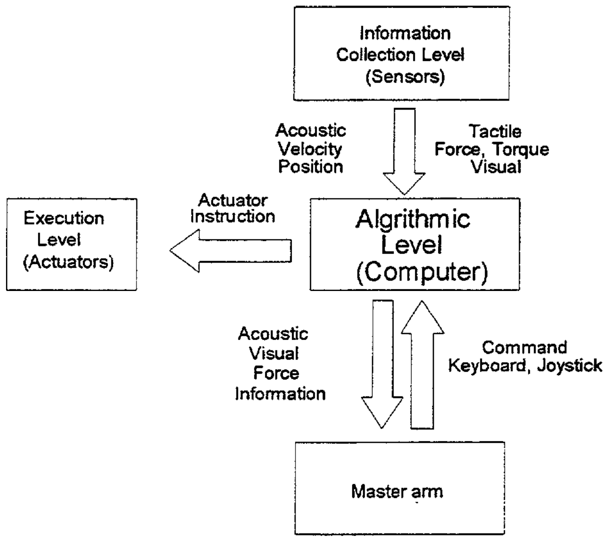


Figure 2.5 The multilevel manipulator control

Advanced automation control is data driven. It is inherently flexible since it is programmable. It contrasts the mechanically fixture rigid automation. The data sources for data-driven automation can be subdivided into two major groups: Models and sensors. Data derived from models typically provide a priority information about robot machines and tasks. Data derived from sensors typical provide on-line information about task performance of manipulators. Broad utilization of both data sources for manipulator arm control typically requires digital computers.

Remote application of manipulators requires flexibility in control and in information management to cope with varying and unpredictable task conditions. The use of data-driven automation in telemanipulation offers significant new possibilities to enhance overall task performance by providing efficient means for task-related controls and displays.

2.2.5 Conventional control methods

Conventional control methods can be classified by the way of control, that is directly control and programmed control.

1. Direct Control

1) Manual operated

The actuator or the control device was controlled by the operator at underwater site. All the information is directly gathered by the operator.

2) Direct Hydraulic

Direct hydraulic control systems are currently the simplest and the most reliable for its hardware. Each subsea function requires a hydraulic flowpath from the surface. Then, actuation of a surface-located mimic display panel results in pressurized fluid being routed through the dedicated flowpath to the selected subsea hydraulic actuator.

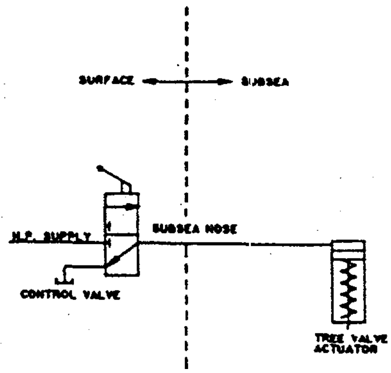


Figure 2.6 Direct closed hydraulic

A closed direct hydraulic control system (Figure 2.6) utilizes a single line between a surface control valve and a subsea function or group of ganged functions. This system can provide individual control over each subsea function or group of functions and inferred feedback concerning subsea operations from pressure switches on the control line and by metering fluid supply and return.

An open direct hydraulic system utilizes also a single line between surface valve and a function, instead of a return line, it utilizes a dump valve subsea, the control fluid dumps direct to sea water. This system improves valve operating time by eliminating the need to flow control fluid back to the surface facility and renews control fluid with each operation, however, the working fluid used in such a system should be environment friendly.

The direct hydraulic system is not suitable to be used ordinary control of complicated system, but only some very special situation, such as hotline backup.

3) Discrete piloted Hydraulic

Discrete piloted control (Figure 2.7) utilizes a signal line between a valve for each subsea function or group of ganged functions. A common high pressure hydraulic supply is used between the surface and the subsea facility.

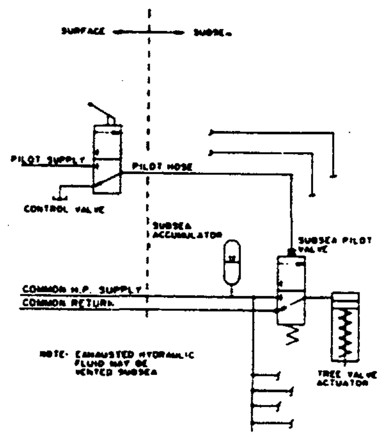


Figure 2.7 Discrete piloted hydraulic

4) *Direct electric*

Direct electric control utilizes every single electrical conductor to each unction, all the control and power are directly controlled from surface. This is relative unusual to be used now, because of the large number of conductors and limitation on electrical equipment for underwater use.

5) *Direct electro-hydraulic*

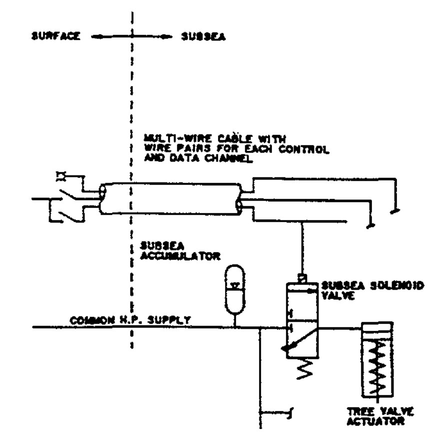


Figure 2.8 Direct Electro-hydraulic control

Direct electro-hydraulic control (Figure 2.8) utilizes a single separate electric circuit in a subsea electrical cable to control a solenoid pilot valve for each function or group of ganged functions. A high pressure hydraulic line normally supplies control fluid subsea.

2. Programmed/Sequence control

1) Sequential piloted hydraulic

Sequential control (Figure 2.9) utilizes subsea pilot valves that switch position in response to signal pressures applied from the surface. Subsea pilot valves are interconnected so that hydraulic pressure is applied to subsea actuators in a predetermined sequence in response to preset changes in signal pressure. Independent, discrete function control is not possible with this system, and there is no ready means of confirming device operation other than by observing fluid flow or pressure build-up. Operating sequences must be determined in advance.

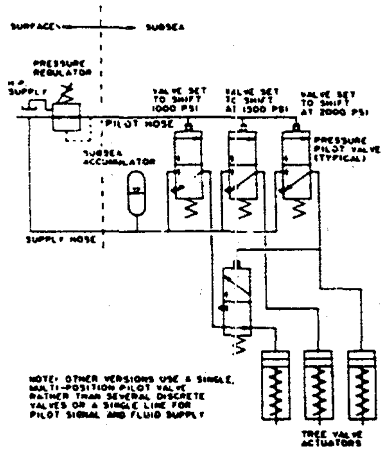


Figure 2.9 Sequential piloted hydraulic

2) Electro-hydraulic multiplex

This system is the most used form of electro-hydraulic control (Figure 2.10). It utilizes dedicated or common conductors to supply control signals (usually multiplexed digital data) and power for the operation of all subsea functions. Electronic encoding and decoding logic is required at the surface and subsea. This approach reduces electrical cable and subsea electrical connection complexity and lends itself to the use of inductive couples in underwater make and break circuits. Sometimes, the electrical signal lines are replaced with optic-fiber cable for better reliable and grater band width. Figure 2.11 shows a schematic of an E-H multiplex control system that uses a subsea hydraulic power unit.

3) Closed loop automatic control

This system is the most used form of numerical control machinery, all the actions and position information are pre-programmed and the sensors are built in for the internal loop feedback. This approach can be used as sub-system of the autonomous or supervisory system.

The autonomous and supervisory control will be discussed in the following sections.

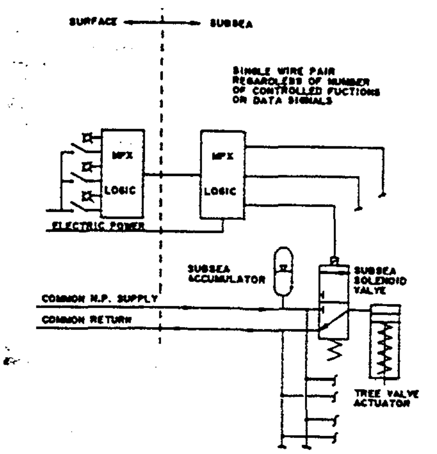


Figure 2.10 Electro-hydraulic multiplex Control

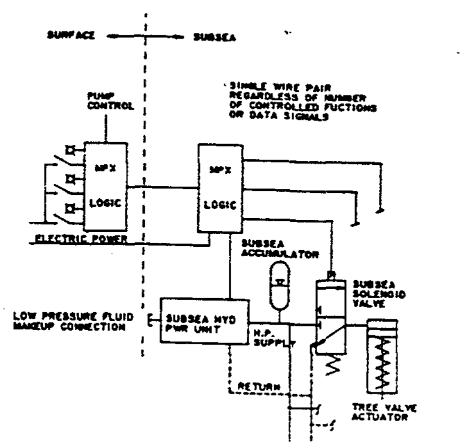


Figure 2.11 Electrohydraulic multiplex control with subsea hydraulic power unit

2.2.6 Autonomous and supervisory control

2.2.6.1 Autonomous control

From the term "Autonomous control", we know that this type of control requires no or very little of human intervention. The control of the system is pre-programmed, the task is well defined. The operation of this underwater working system is more or less like the industrial robot. The major difference is that since the condition under water is changeable and can not be defined very well, the autonomous controlled systems have to have certain ability to adapt itself to the outside environment and at same time, send and/or receive some information between the vehicle and surface station. The system is utilizing some self-sufficient technology (Figure 2.12). It consists of a surface control station, a control system and power system subsea. Hydro-acoustic signals are transmitted through the water between the subsea system and the surface station. The surface station for autonomous control is actually a monitoring station.

The biggest advantage of this system is the elimination of the umbilical gives the vehicle great freedom. The autonomous controlled system can be used for under ice operation or military mission. The current autonomous control is not really "autonomous", it can only execute a number of simple tasks autonomously. A complete automation is possible only in structured environments, such as in the industrial applications or the very simple procedure like stow the manipulator in a specific place, where teach-playback capabilities are sufficient to perform all the required tasks. If the work is conducted in a complex environment and performing a complicated task, the best method of control is supervisor control.

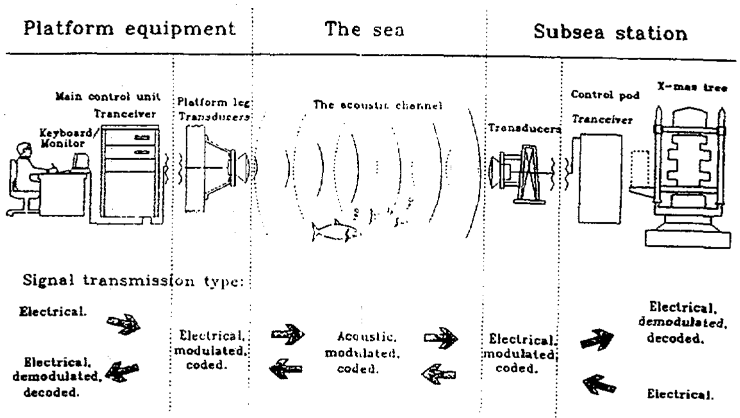


Figure 2.12 Autonomous control

2.2.6.2 Supervisory control

The underwater working systems are normally mobilized. The operation requires very high operator skill and concentration, because the master-slave/Joystick control only uses the low level automation. This makes execution of complex tasks tiring and time consuming, or even not feasible; sometimes the visual feedback is insufficient.

The supervisory control methodology is the best way to solve this kind of problem. In this approach, a computer is introduced between the operator's commands and the underwater part of control system. The machine supports the operator during task execution, giving the global man-machine system enhanced capabilities in terms of productivity and of range of feasible tasks. In moving base operations, such as operating a manipulator in a programmed sequence on a ROV; the compensation is performed automatically by the computer.

The main idea in the supervisory control concept is to treat human as a particular element of the control system. His action is supported by means of a form of automation suited to man's characteristics. The machine has to perform as computations and repetitive commands, leaving the high intelligence part, such as task planning and monitoring to the human operator.

Supervisory control means that one or more human operators are continually programming and receiving information from a computer that interconnects through artificial effectors and sensors to the controlled process or task environment when the computer closes the loop that excludes the human operator the computer is working as autonomous controller for the loop.

The definition shows that computer transforms information from human to controlled process and from controlled process to human. For the operations while the computer close a control loop that excludes the human, then the computer is working autonomous controller for some variables at least some of the time.

The accompanying figure (Figure 2.13) characterizes supervisory control in relation to the extremes of manual control and full automatic control.

Supervisory control may take many forms, but in general allows the operator to specify some of the desired motion symbolically instead of by analogy. The computer interpreting the symbolic commands then issues the coded commands. This mode of operator interface results in a hybrid between teleoperator and robot. Now a new term called telerobot.

Since all the activities for supervisory control are occurring at distance, so the actual surrounding of the underwater equipment should have one or another method to present to the operator. For this purpose, a few concepts could be used.

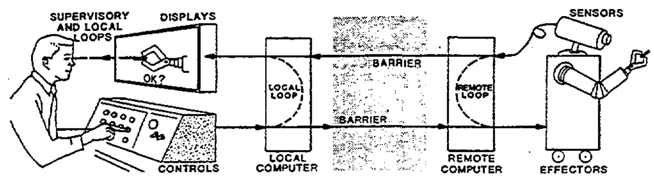


Figure 2.13 Conceptual supervisory control

1. Telepresence

Telepresence means that the operator receives sufficient information about the teleoperator and the task environment, displayed in a sufficiently natural way, that the operator feels physically present at the remote site, for example, 3D video camera, microphone, temperature meter, etc..

2. Virtual presence, virtual environment, virtual reality

Virtual presence, or synonymously a virtual environment or virtual reality or artificial reality, is experienced by a person when sensory information generated only by and within a computer compels a feeling of being present in an environment other than the one the person is actually in. The position and orientation of the working system are updated according to the information fed back through the feedback loop.

With sufficiently good technology a person would not be able to discriminate among actual presence, telepresence, and virtual presence. At current, some of the system is just a combination of telepresence and virtual presence.

2.3 Structure of underwater control system

The underwater control system consists of surface control station (console), power distribution unit, communication unit, subsea power unit and actuation system (Figure 2.14).

A typical control system is normally consists the following sub-system.

- Surface control station/console
- Signal transfer media
- Power transfer media
- Power conversion device
- Data acquisition device
- Control element
- Actuator

A control system needs to give the actuation system instructions for the movement of the system according to the operator's instruction, pre-programmed or online programmed. At same time, the control system is also required to collect information that represents the status of the actuation system and the surrounding environment.

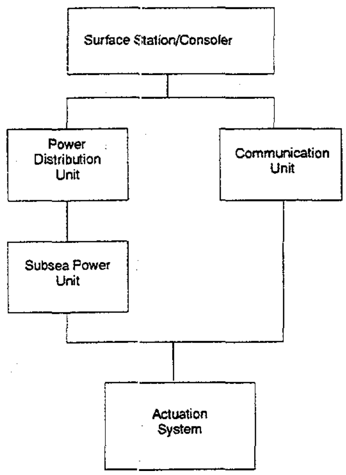


Figure 2.14 Subsystems of underwater control system

1. Surface control station

The surface control station is the most important subsystem in the whole equipment. It consists control panel for input of instruction, monitoring process and status of system, information processing and storage. When the surface control station is a stand alone equipment, it will consist power distribution unit and communication unit. When secondary power source is used, it will also consist a secondary power source generating unit which is normally hydraulic or pneumatic. Figure 2.15 shows the main components in the surface control station and relevant subsystems.

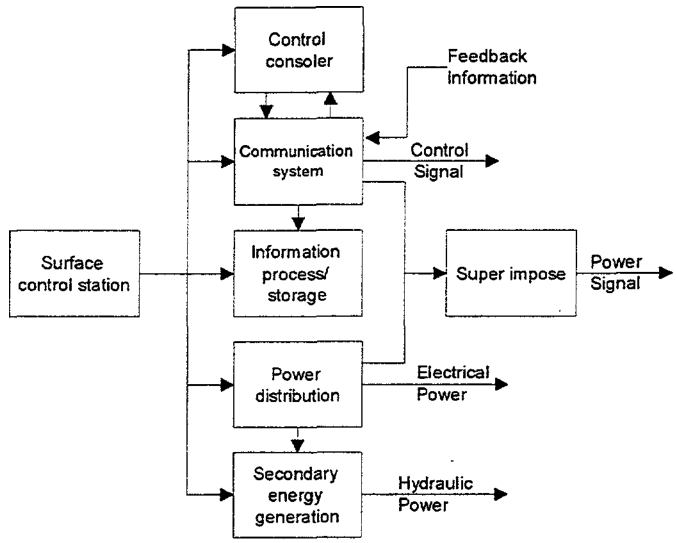


Figure 2.15 Main components in surface station

2.3.2 Surface control station

There is a control room in the mother ship (support vessel), that contains the electronics, computers, monitors. If the ROV installed manipulator, normally the master arm or joysticks or other control board is also located in that room. Figure 2.16 is the surface control room of DOLPHIN-3K.

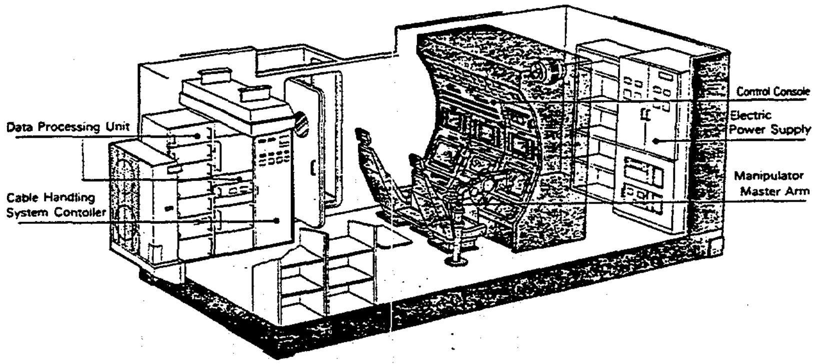


Figure 2.16 The surface control room of DOLPHIN-3K (Courtesy by JIMTECK)

2.3.3 Underwater navigation system

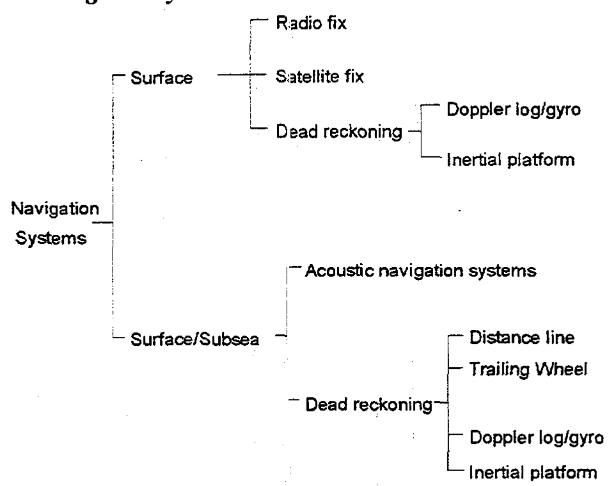


Figure 2.17 Navigation systems

Underwater navigation system's functionality is to give host system the reference of position, attitude, heading, vehicle and current velocity. The devices used for these purposes are depth sensor, gyro, etc. Figure 2.17 listed some of the navigation devices.

2.3.4 Underwater communication system

Communication with underwater robots can be viewed in three contexts:

1) Shore to surface, which involves command and control from a shore based station to the mother-ship positioned at sea

2) Surface to Depth, which involves the communication between the mother-ship and the submersible

3) Diver to vehicle, or vehicle to vehicle in the case of multiple vehicles, which involves communicating with the diver from the submersible or the mother ship.

New fiber optics technology has established excellent communication capabilities for tethered vehicles. The evolution of the new autonomous robotic vehicles demands a greater degree of sophistication, to establish a tetherless communication. From Figure 2.18, we can see all the different configuration of underwater control system.

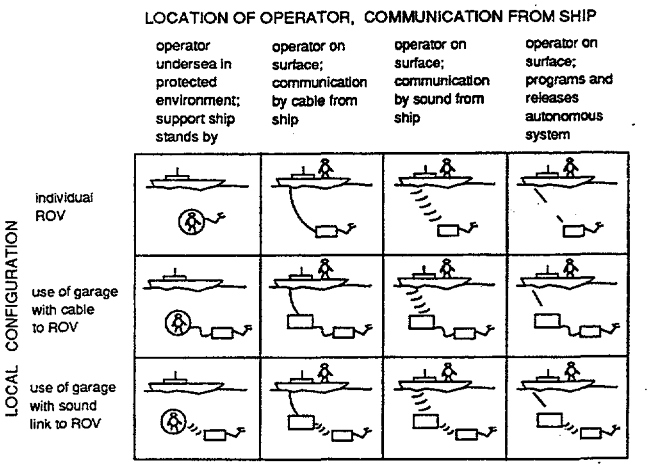


Figure 2.18 Alternatives of underwater control setup (Sheridan, 92)

2.3.5 Data acquisition and sensoring Systems

Improved force and torque sensors have made it possible to introduce force feedback in manipulator control. The new advances in tactile sensing are yet to find applications in underwater missions but would be of a great benefit in exploratory missions. Technomare has developed a new TV-trackmeter based on stereoscopic vision.

Acoustic sensors have received widespread attention with their potential superiority over optical systems for underwater applications where scatter is a major problem. Ultrasonic transducers have been used for many years for underwater applications such as range measurements. Coupling procedures and advanced software and hardware for signal processing have given a new dimension to the acoustic sensors, with a capability of providing a 3-D information at low cost. In particular, short range vision close to the sea-bottom can be more effective with acoustic imaging than optical imaging. One of the interesting projects in this area is being undertaken by STATOIL in collaboration with Technical University of Denmark to develop a novel acoustic sensor for application to underwater robots. The robot vision system envisages using two frequencies-150 kHz and 1.5 MHz. The lower frequency will be used for low resolution, high speed imaging and the high frequency for high resolution imaging at short range.

One of the major research issues in developing efficient systems would be the sensor fusion in which multiple sensors are used to capture the same information.

2.3.5.1 *Data monitoring and registration*

The data from the different ROV sensors and inspection equipment are monitored at the control console by the pilot and the inspector.

The following equipment is used:

- Lamps. The lamps may have different colors and may be positioned in a pattern relative to each other. The lamps may indicate that motors are on or off, valves are closed or open, etc.
- Digital displays. These displays present one parameter in form of a number with a given number of digits. Digital displays may present data like ROV depth, heading,etc.
- Analogue displays: There is a variety of types ranging from traditional meters with a pointer and a scale to modern light emitting diode bar displays where the pointer is replaced with a light point. Data like electrical currents and oil pressures, but also depth and heading may be presented on such displays.
- General CRT displays (Cathodic-Ray-Tube), are used to present TV pictures and sonar pictures. Other data like time, depth heading, etc., may be superimposed on these pictures. CRT displays are also used to present data from computers in the ROV system.
- Graph CRT displays (Computer monitors) are used to display many of digitized signals, such as gauges, meters, video and sonar images, navigation fix, depth, heading, course, and speed, etc..

2.3.5.2 *Equipment used for data registration:*

- Manual logs. one or more persons write relevant data on paper. These data may be time, position, events, etc.
- Video tape. The TV pictures and eventually sonar pictures are recorded on video tape. Time, position and other relevant dada that are imposed on the pictures are used as reference.
- Photo cameras are used to record interesting information that is displayed through the TV system of the ROV. Time, position, frame numbers and other relevant dada that are imposed on the film for reference.
- Paper recorders are presenting data from one or more sensors on paper sheets with time axis along the sheet.
- Printers and plotters are used in connection with computers in the data monitoring and registration system. Printers are used to print messages, events tables of data and simple diagrams. Plotters are used for graphical presentation of data.
- Digital storage, magnetic disk, optical and non-volatile optical WORM drives (Write Once, Read Many) are used for digitized signals. Unlike analog recordings, there is no signal drop out, no loss of quality, no introduced noise. As long as the digital values are viable, the recorded signal remains uncorrupted. The advantage of a digitized signal system is that the data can be a part of an integrated data management system. Multiple drives can also be ganged together to provide a data bandwidth as

large as is required to record the multiple channels of sonar image, telemetry, single frame video, VCR indexes, digital photos, and other sensors' signals.

2.3.5.3 Sensors

The control of underwater equipment needs the feedback of the information, such position, velocity, orientation, force and torque information. The sensors are classified as position sensor, velocity, orientation sensors, force and torque sensors. The most important sensors are the position, velocity sensors. If the force and torque control is required, the force and torque sensors are also very important.

1. Feedback sensors for velocity and position

Feedback sensors are needed on an underwater equipment for feeding back the position and velocity of motion of the various actuators. The information is necessary to maximize the dynamic accuracy, to accelerate and decelerate the motion, to stop it at a programmed position, to signal the commutation sequence of a brushless DC servo motor, and so on. In the last case, the sensors are usually referred to as commutation sensors. Hall generators, which are described below, are frequently used for this purpose. Other feedback sensors are potentiometer, tachometers, resolvers, and optical encoders. Table 2.3 summarizes some of the velocity and position sensors commonly used.

Table 2.3 Sensors for Position and Velocity measurement

Type of Sensor	Principle	Signal type	Application area	Usable underwater
Commutation	Hall effect	Analog (magnetic fields)	Rotation speed and/or angular for Servo-motor Electra-optical switch	Yes
Potentiometer	Resistance with relation of position	Analog (resistance)	Position - Linear and rotary actuator	Yes
Tachometer	Voltage generating	Analog (Voltage)	Rotation speed - Rotary actuator (motor)	Yes
Resolver	Voltage function	Analog (Voltage)	Angle - Rotary actuator	Yes
Optical Absolute Encoder	Light pulses	Digital	Position, angle and velocity - Linear and rotary actuator	Not recommended
Optical Incremental encoder	Light pulses	Digital	Relative position and angle - Linear and rotary actuator	Not recommended
Proximity	Electra-optical Electromagnetic Acoustic Hall-effect Capacitive	Digital (Switch signal)	Relative position and angle - Linear and rotary actuator, counting	Yes

2. Feedback sensors for force and torque

The acquisition and use of both visual and nonvisual sensor information in remote manipulator arm control is of critical importance. Visual information is obtained directly or through stereo or mono television, and can be supplemented with information from ranging devices. Visual information for manipulator arm control is of geometric nature. It relates to the gross transfer motion of the mechanical arm in the environment and to the position/orientation of the mechanical hand relative to environmental or object coordinates.

Nonvisual sensor information supplements the visual information and is needed in controlling the physical contact or near-contact of the mechanical arm/hand with objects in the environment. It is obtained from proximity, force-torque, and touch-slip sensors integrated with the mechanical hand. These sensors provide the information needed to perform terminal position & orientation and dynamic compliance control with fine manipulator arm motions. The control information from these sensors is directly referenced to the coordinates of the mechanical hand. The acquisition and use of nonvisual sensor information represent a major challenge in advanced remote manipulator control technology development.

1) Force-Torque sensing

Force-torque sensors measure the amount of force and torque exerted by the mechanical hand along three hand-referenced orthogonal directions. These sensors also measure forces and torques applied about a point ahead and away from the sensors. These sensors are mounted at the base of the mechanical hand.

Force-torque sensors utilize mechanical force-summing elements that convert applied force into a small mechanical displacement. The mechanical force-summing elements are linked to electrical transduction elements. Table 2.4 summarizes some of the force-torque sensors. Strain gages (in particular, semiconductor strain gages) are preferred transducers for six-dimensional force-torque sensors integrated with manipulator hands (Figure 2.19).

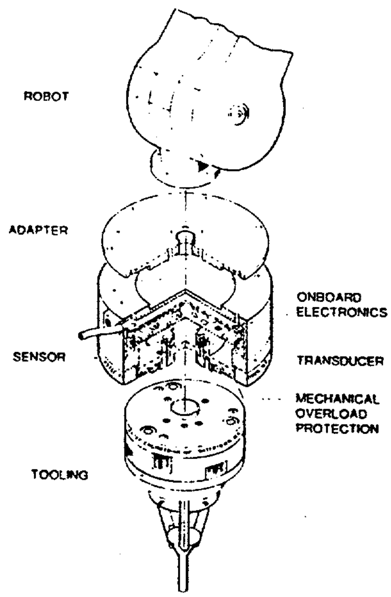


Figure 2.19 Six-axis force sensor (integrated with wrist)

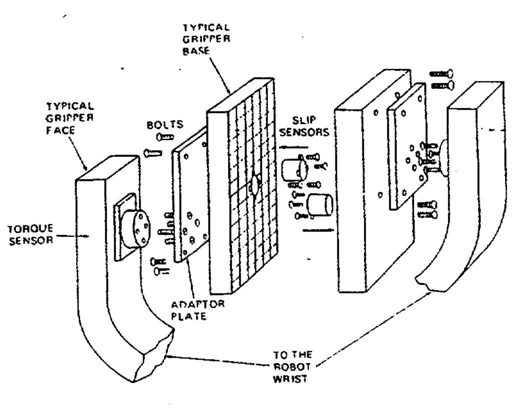


Figure 2.20 Six-axis force sensor (on gripper)

Figure 2.20 shows the gripper of a robot equipped with two torque sensors in the gripper base combined with two sip sensors in the gripper faceplates. Torque as well as slip sensors are magnetoelastic. They are designed for a large industrial robot that has a load capacity of 180 kg.

The torque sensors can each measure a torque of up to 135 Nm in a package 2.5 in. in diameter and 20 mm in high. The top plate or turret of the torque sensor in this figure is mounted to the gripper face.

Table 2.4 Sensors for Force-Torque and Tactile sensing

Type of Sensor	Principle	Signal type	Application area	Usable underwater
Strain Gages	Resistance change	Analog	Force or/and Torque - Linear and rotary actuator	Yes
Silicon Strain Gages	Resistance change	Analog	Force or/and Torque - Linear and rotary actuator	Yes
Conductive Membrane	Point connection	Digital	Tactile - End effector, Body surface	Yes
LSI (Large Scale Integrated Circuit) Sensor	Point connection	Digital	Tactile - End effector, Body surface	Yes
Silicon touch sensor	Piezoelectric	Digital	Tactile - End effector, Body surface	Yes
Magneto-resistive skin	Conductivity as function of Magnatic field	Analog	Tactile - End effector, Body surface	Yes
Ultrasonic force Sensors	Thickness change	Analog	Tactile - End effector, Body surface	Yes
Magnetoelastic Sensors	Magnetic field change	Analog	Tactile - End effector, Body surface	Yes

3. Tactile sensors

Tactility is capability of an object to be felt or touched. For the purposes of robotics, tactility is the feeling of the presence of force, torque, and slip.

The ability to construct, maintain, and repair structures in hazardous or inaccessible environments are a prerequisite for the large-scale human utilization of space, the oceans or the arctic regions. This ability is also essential for unconventional applications, such as the repair of components in a nuclear, biologically or chemically hostile environment. To achiever such aims requires some form of remote automation. For all practical sub-sea purposes sensors can only be sight, sound and touch.

Locating, identifying and manipulating objects on the sea-bed is never easy. When the bottom is soft mud, or the water is silted due to strong tidal currents or a nearby river mouth, the task becomes even more difficult. The low ambient light levels and marine growth also add to the problems. In such conditions, one of the main tools for sub-sea remote operation, the visual sensor--underwater camera, is sometimes unusable. So a touch sensor that can operate in any visibility, even immersed in the sediment on the sea bed will be very important. A suitably designed touch sensor could also penetrate marine growth until it reached the true surface of the object.

One of the main advantages offered by touch sensing is its ability to provide direct range and position data, kinesthesia. This is analogous to the sensory feedback one obtains from one's hands when wearing thick gloves. Remove the gloves and one is then able to utilize the finger tips to register pressure, vibration, temperature and texture these are known as the cutaneous senses.

Touch sensing is still in its early stages of development and most of the effort so far has gone into sensor design rather than sensor data processing. Much of the research since the late 70's has involved using touch sensors solely for shape recognition verification of the target object. Table 2.4 lists some of the skin type tactile sensors currently developed for robotics research and application.

Touch sensors can be conveniently divided into groups by their complexity:

- Simple touch: Contact with one or a few touch probes (tactors with either a linear or binary output.
- Gross tactile: A matrix of simple touch sensors, need not be closely packed.
- Tactile: Skin like sensor which a very high density of sensors and some ability to conform to surface shape.

Figure 2.21 shows the concept of the skin. The concept of LSL is shown in Figure 2.22.

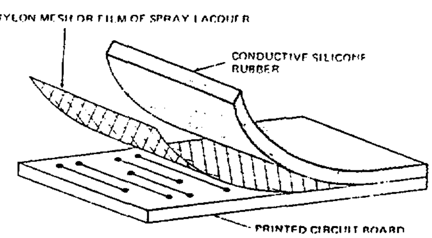


Figure 2.21 Skin with conductive elastomer.

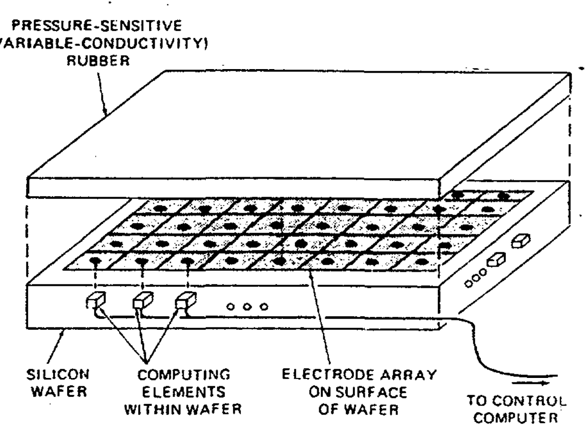


Figure 2.22 LSI sensor

(1) Silicon Touch Sensor

The development of micromechanics permits shaping silicon in three dimensions, so it made it is possible to use the silicon's piezoelectric characteristics and moves physically in response to pressure. The very thin silicon membranes that made by the micromechanics can be strained by the slightest touch, and producing electrical signals. Transensory Devices, Inc. uses this process in making silicon touch sensors. It permits mass production of minute structures with extremely high precision. By combining these structures with an onboard microprocessor, signal processing can be performed on the touch sensor itself, increasing the overall system accuracy, control, and reliability.

The following figures show the construction of magnetoresistive skin (Figure 2.23) and an ultrasonic method (Figure 2.24).

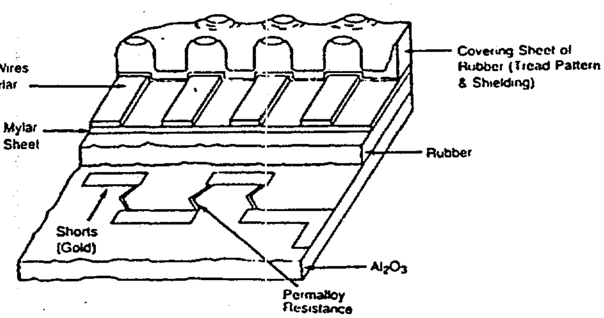


Figure 2.23 Construction of magnetoresistive skin

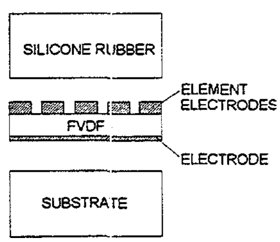


Figure 2.24 Array construction of ultrasonic sensor

In the sub-sea environment most components are large so to be of real use tactile sensors either have to be very large and deployed passively, or small and deployed actively. Many various types tactile sensors have been designed, but wear still remains a problem. Wear resistance is only achievable at the expense of sensitivity. The other problem yet to be solved is the combining of the two desirable deform over the object of interest and skin-like properties to feel(measure) the object.

Gross tactile sensors are those that are too complex to be classified as a simple touch sensor yet not sufficiently skin-like to be true tactile sensors. They offer a compromise between the rugged, low resolution simple touch sensors and the high resolution, fragile tactile sensors. This class of sensor would also be used in an active deployment mode. If the size and distribution of the individual tactors in the sensor are matched to the target object, then using gross tactile sensor can greatly reduce the number of sensor placing needed for satisfactory identification than using simple touch sensors. If there is a mis-match between sensor size and object size, especially if the object is very large compared to the sensor, a gross tactile sensor would have to be deployed in a manner similar to a simple touch sensor. Due to the increased size a gross tactile sensor would not be as effective in penetrating any matter immediately surrounding an object.

The few substantial tactile systems that are commercially available for research and industrial use are either too cumbersome or too fragile for practical use.

2.3.5.4 Attitude sensors

The attitude sensors are the sensors providing information to the ROV pilot and to the auto pilot concerning ROV heading, water depth, height above bottom and roll and pitch angles.

The heading sensors include:

- Magnetic compass with analogue or digital repeater in control console, or direct reading with TV camera.
- Gyro compass with repeater in control console.
- Fluxgate compass.
- Rate gyros and other sensors for ROV stabilization.

All of the sensors mensioned have their own problems, there is not single one of them is best for all the operations: The magnetic compass has small dimension, fast responsible time, but it is unsuitable for using in the area close to steel structure members and pipelines or in the earth's magnetic field.

The gyro compasses are very suited for ROV operations. They are accurate, short operational settling time and suitable to auto pilot control, but the dimension of it is rather large and the initial settling time is too long.

The rate gyros and similar sensors are only suitable for short vehicle stabilization duration.

The acoustic echosounder is used as height sensors, the acoustic echo-sounders with sound frequency varying from the kilohertz to the megahertz range and lobes from several degrees to less than one degree wide.

The acoustic echosounder is really good when the ROV transport close the bottom and for height stabilization during pipeline inspection. But there are still some problem when the acoustic echosounder is using. The frequency of it is the most difficult problem. The lower frequencies normally have good ping receipt and long range, but low accuracy. The higher frequencies have good accuracy, but insecure ping receipt in turbid water and short range.

Pressure sensors which utilizing different measuring principles are used as depth sensors. And the inclinometers which based on pendulums or torque balances are used as pitch and roll sensors.

The pressure sensor has enough accuracy for general use, but if only one depth sensor is used it will make the depth keeping difficult because the displayed depth variation due the wave's affection. So sometimes it is necessary to use a combination of accurate depth sensor and accelerometer to provide a better reference for depth keeping.

2.3.5.5 Image generating instrument

1. TV cameras

TV camera is the equipment used for orientation of ROV and for visual inspection and survey, to provide the video documentation for later use. The lights' configuration is used to provide enough light for TV camera.

The closed circuit television (CCTV) is the primary visual sensor of ROV, and color TV is also sued in commercial underwater applications.

Both of them have their advantage and disadvantage. The monochromatic TV has higher resolution, lower light requirement and larger range compare with color TV. But the underwater lighting cannot improve contrast of a black and white image if the area is covered by red rust or green paint. The color TV is the best alternative for such kind of operation. Resolution of both of them is lower than photograph.

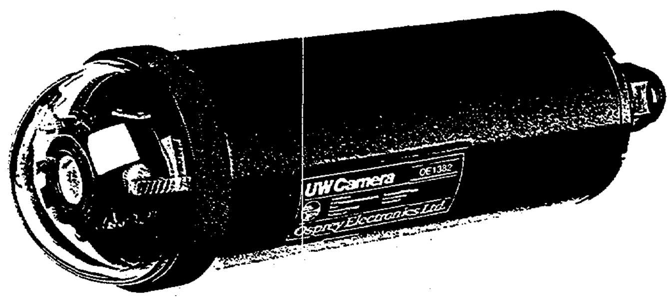


Figure 2.25 Color CCD underwater TV camera with built-in Pan, tilt and classis rotate

2. Acoustic viewing

Acoustic imaging system is used for navigation, obstacle avoidance, position and inspection. It has larger range than TV camera and limitation of light, and can see through marine growth. But it is not suitable to observe the object close the structures and ROV because of the reflections, shadows multiple transits and the influence of the acoustic noise from ROV. The quality of imaging is much worse than TV picture or photography. Figure 2.26 exhibits a typical configuration of color acoustic viewing system. The acoustic viewing system together with TV camera, laser viewing system, all most all the visual can be obtained.

2.3.6 Computer system

Computer system is the core of a modern control system. The system provides most of the low level instruction such as feedback information gathering and operator's input processing. The computer system normally consists CPU (Central Processing Unit); internal data storage;

external data storage; data communication bus and display, etc.. The computer system can use a single chip computer, with 8-bits, 16-bits capacity, PLC, or commercial or purpose built computer. More about computer system and communication will be discussed in later chapters.

In modern underwater control system, in order to fullfil the increasing requirement of processing capacity of information and redundancy, multiprocessor system was introducted. The multiprocessor system can be classified to multiprocessor system and distributed multiprocessor system.

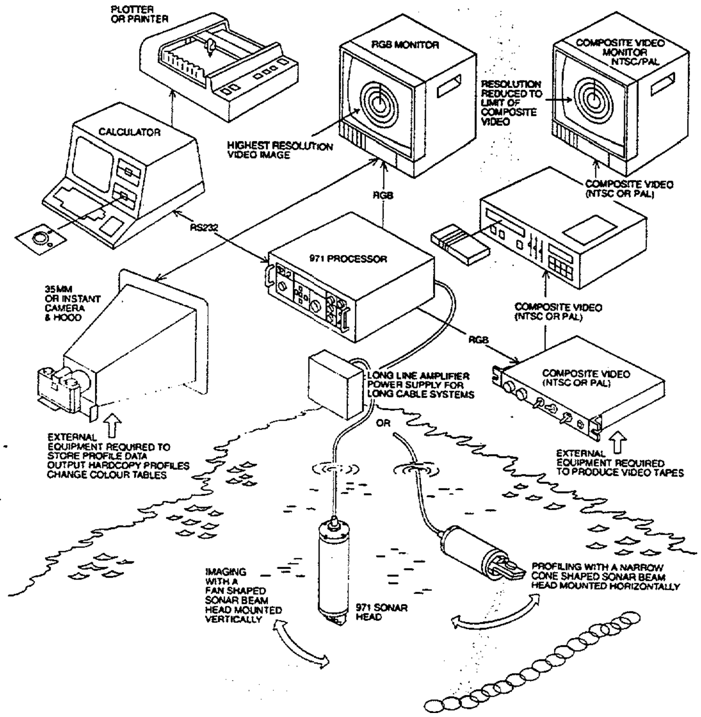


Figure 2.26   Typical color imaging sonar system

The multiprocessor system contains two or more processors of approximately comparable capabilities. They share access to a common memory; Input/Output (I/O) channels; control units and peripheral devices. The whole system is controlled by a single operating system. When each processor in a multiprocessor system has its own local memory and its own system software, where all the local memories are distributed in the local sites, and the shared memory is only to share data between the network processors, not for program execution, then the system is a distributed multiprocessor or distributed mini-/microsystem.

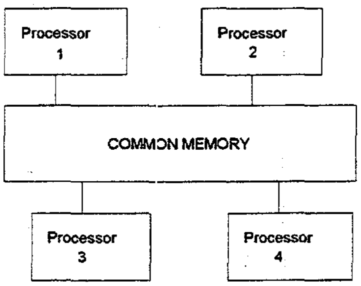


Figure 2.27 Central multiprocessor system

With multiprocessor system, the control program can be divided into smaller units and result less complex control programs. Higher processing power can be achieved with lower prices, since the price of the processing power for large computers is higher than the price for small sized computers, both for the hardware and the software. Not only that, the redundancy technique for central control systems is much more expensive than for the distributed control systems.

One of the main advantages of the distributed system, is its flexibility to change any node (e.g., PC, PLC, etc.), when a process needs higher processing speeds or more memory capacity. Modernization is easier, especially with the rapid development and improvement of the computing systems. Another advantage of the distributed system is that it is easy to adapt different configurations, since each node is dedicated to a specific task. The system has high reliability, since if any node becomes out-of-order, it can be changed easily. One disadvantage of the distributed system concerns the complexity of the communication software and the interface with the operative system's single processor, which administers the internal processing operations and the peripheral drivers. Another difficulty is localizing errors when they occur at any place in the system network.

As mentioned before, these units of equipment need to communicate to realize the functioning of the working system. There are several networks to provide the communication facilities for the distributed system interconnections. We will discuss them in later section.

2.3.7 Umbilicals, cables types and requirement

1. Hydraulic control lines (Umbilical).

Hydraulic control lines generally comprise of reinforced thermoplastic hoses; steel tubing or pipe bundled together with a protective jacket and or armor.

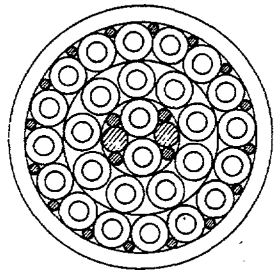
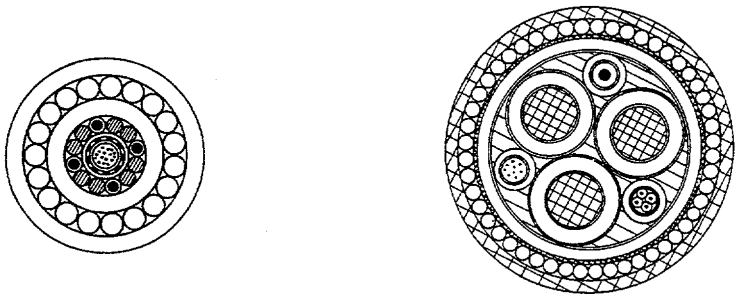


Figure 2.28 Typical construction Hydraulic control umbilical

2. Electrical/Optical Control Lines (Umbilical).

Electrical control lines generally comprise of power and signal conductors cabled together with an appropriate jacket and armor.



Optical fiber cable Combined power and signal cable

Figure 2.29 Typical construction of Electrical/Optical umbilical

3. Composite control bundle

A composite control line contains both hydraulic hoses and electrical/optical conductors in one single bundle. Provisions are made in the lay-up configuration of the hoses and conductors to allow movement, expansion, and elongation contraction of hydraulic hoses without damaging the electrical conductors.

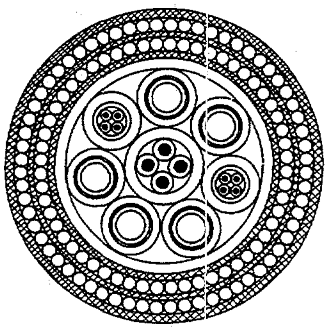
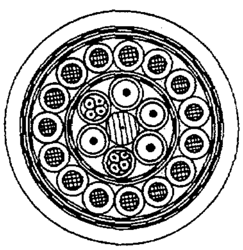


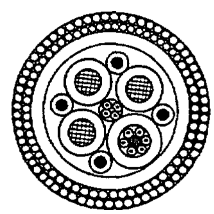
Figure 2.30 Typical construction of Electro-Hydraulic umbilical

4. Combined lifting and control umbilical

In order to reduce the lines involved in deployment, many of the underwater equipments are deployed by the same umbilical for control. The combined umbilical normally consists both control lines and counter balanced armour to take up axial force occured during deployment and handling. A special heave compancated winch or crane will be used with such umbilical to achieve safe operation.



ROV Umbilical



Lift umbilical for TMS-system

Figure 2.31 Typical construction of combined lift umbilical

2.3.8 Hydraulic valves

Hydraulic valves are the basic control elements for a hydraulic driven system. In order to control the speed, direction, logic function, etc., a combination of different valves can be configured for different functionality. The basic types of valves are directional, pressure control valve or flow control valves.

2.3.9 Control fluids and requirement

The control fluid is a power transfer media for a hydraulic driven system, the fluids used in an underwater equipment has two categories, water based and oil based. The water based fluid is subjected to discharge into water, and oil based fluid is restricted for forbidden to discharge into water. There are two types of oil base fluids are available for subsea control applications -- water-soluble oil and petroleum based oil.

Other control fluids, such as synthetic hydrocarbons, hybrids, etc., can also be used when special requirements are involved.

2.3.10 Electronics instrument

The underwater working systems need to send and receive a large quantity of information, so the device used to transmit information is very important.

Control signals to the underwater equipment and feedback signals from the underwater equipment are normally digitized; time multiplexed and coded prior to transmission over a coaxial cable or a twisted pair in the umbilical/tether cable. The latest research shows using radio wave to transfer signal from or to underwater working system is possible.

2.3.10.1 Signals to be transmitted

An oceanographic data storage and management system is a system for recording, viewing, and evaluating multi-media data. System integration includes side scan and sub-bottom sonar, navigation and telemetry data, GIS data, annotations, photographs, video, mission planning, charts, CAD drawings, as well as calculated numeric data, such as ship or ROV telemetry vectors. Among the information the underwater equipment needs to communicate with surface control station:

- Video picture
- Attitude
- Orientation
- Position
- Sonar image
- Temperature and pressure

There are normally some spare channels on the multiplexing systems for digitized analog signals and for simple on/off signals, which can be used for control of and signal retrieval from auxiliary equipment.

Video signals are usually transmitted on separate coaxes in the umbilical/tether-cable. On some systems two or more video signals are frequency multiplexed and transmitted on one line multiplexing of video and other signals also occur.

Special inspection equipment is often delivered with a multiplexer for its control, monitoring and measurement signals. It is therefore prepared for transmission on a separate coax or twisted pair.

The reason for introducing multiplexers is to increase the transmission capacity of the signal conductors of the umbilical/tether cable, or to reduce the required number of signal conductors and thereby providing the possibility of reduction of umbilical/tether cable's diameter and reduction of the number of connectors, penetrators, slip rings, etc.

The signal resolution and updating frequency provided by the multiplexers is seldom a limiting factor.

Noise and interference is a problem with most ROV systems. The video signals are easily disturbed by interference from power conductors in the umbilical/tether cable when AC power is used and from other signal modulators/transmitters.

Additional noise in the extremely important video signals most ROV transmission systems are causing signal quality deterioration due to bad frequency and phase response of the transmission channel.

2.3.10.2 Signal transmission and network

Any type of system needs to have command to instruct them how to work. For the systems we discussed so far, they are normally located distance from the operator, therefore transfer of commanding signal is another major issue in underwater control system. Following sections discuss type of signals should be transmitted and the methods of transmitting them.

1. Method of signal transmission

We have discussed before that an underwater control system needs many feedback signals, amoung them, video signal, audio signal, signals from various sensors and transducers, attitude sensering device, etc.. In order to control the system, the operator needs also give instructions regarding the operation, and those instructions will be translated into certain type signal ready to be transmitted. There are many ways possible ways to transmit such signals, such as:

- acoustic signal
- electrical as power and signal
- hydraulic pressure as power and signal
- superimposed signal/electrical

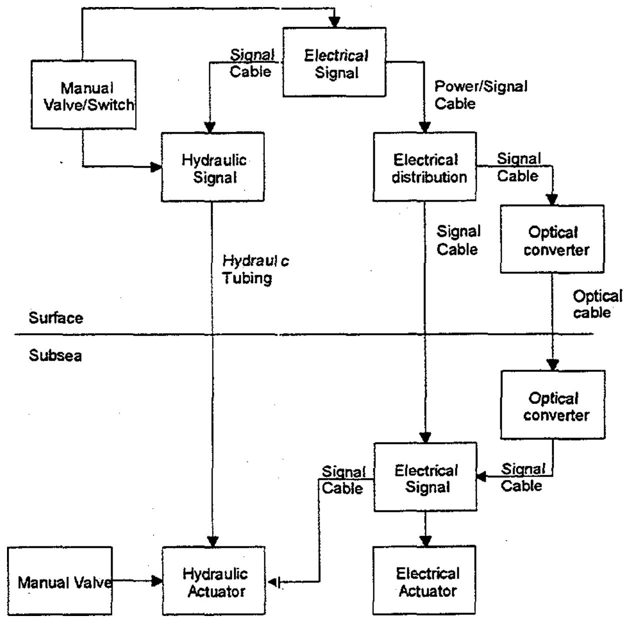


Figure 2.32 Transfer of Signal

1) Acoustic signal

One of the possible, maybe the only way of communicating with AUV is through acoustic link, since the vehicle has no physical link with the surface control station and other type of radio signal can not penetrate water to the working depth. Through this link, the operator can gather sufficient information of the vehicle's status and instruct the vehicle to perform certain pre-defined task or maneuver. The acoustic signal is transmitted through transponder arrays, repeaters from and to vehicle. The problem for acoustic communication is that the bandwidth is very narrow, and the transponder arrays, etc., have to be built from before. An undergoing project in Norwegian Institute of Technology, MOBOTEL, is developing a set of technology to be used in Model based AUV operation. One of the subject is to transmitte control signal and environment image through a bandwidth of 100 bit/sec. The result from the research is very interesting, they can re-construct really high quality image from very little information. Further research still has to be conducted in order to achieve the aimed goal of fully model based AUV supervisory control via acoustic communication link.

2) Electrical as power and signal

Since the underwater equipment with simple functional requirement does not require complicated signal conversion, so the most practical way is to send electrical power directly to each of the function, therefor signal and power transmission are combined into one electrical cable.

This type of signal transmission can only be used for those systems have very small number of function and working in shallow water. While the increasing of number of function and depth, this method will become unreliable and expensive. However, from reliability and cost point of view, this method is better than directly hydraulic pressure signal with similar configuration.

3) Hydraulic pressure as power and signal

For some special underwater equipment, some companies concerned about electrical equipment's safety at subsea. They demand no active electrical equipment should be presented subsea, then the only solution for such a request is to send pressurized hydraulic fluid direct to subsea valves.

Among surface controlled hydraulic system, there are directly hydraulic actuation and pilot hydraulic actuation. The different is that directly hydraulic actuation has a supply line and return line for each function (sometimes the return line can be common), but the pilot hydraulic actuation sends pilot pressure signal to pilot valves. The pilot valves control each function and the hydraulic supply and return lines are common for all the functions.

The pilot hydraulic actuation is better than directly hydraulic actuation because of smaller size of hydraulic tube and less pressure lose. But both of them have limited operation range and limited number of functions. With long and large size hydraulic umbilical, the reliability of the system becomes quite low.

4) Superimposed signal/electrical

Today, there is also a special technique of combining power and signal, that is to superimpose signal on to the normal electrical AC power. With this technique one do not need a separate signal line, therefore the construction and the cost of umbilical are greatly reduced.

This technique uses the base frequency of the AC power as base carrier frequency, so any unsteady frequency, noise or crosstalk from the cable will greatly reduce the cable's communication capability. In order to keep a steady frequency of carrier current, a large capacity rectifier needs to be installed between power source (power line or generator). This type of rectifier is normally very expensive. In addition, a separation device and transformer need to be installed subsea, this causes addition problem of electrical isolation and space requirement.

5) Multiplexed electrical/optical signal

The most common way of signal transmission of complex underwater equipment control is to transmit control signal and feedback signal through electrical cable and optical fiber cable. The uplink and downlink signals are coded according international or company's communication protocol. So far only copper cables are commonly used, but optical fiber cables are also increase their popularity.

Multiplexing signal arranges all the signals in certain pattern (protocol) and transmit them; one or both ends can initial the transmission.

The biggest advantages of optical fiber cables are the large communication capacity, long distance communication and small size. But it is more expensive compare with copper cable, and technically more complicated.

Figure 2.32 illustrated different ways of communication. Manual operation of valve and switch is normally for emergency backup in case of system failure.

2.3.10.3 Network systems

In a modern control system, there is a large number of control elements and sensors need to communicate to each other, To ensure that all elements can communicate on time is important. Communication is also occurring between different processing units and computer parts, and many of the modern control elements and sensors have processing capacity of their own, those are so called intelligent devices. Communications between all those mentioned devices demand some sort of network system.

The following sections briefly introduce some of network type (Radwan, 88).

1. Shared Memory Interconnection

This is a common way to interconnect computers through a shared memory. The shared memory is usually a primary memory, but it can also be a disk. Each node in the network is connected to the shared memory by a dedicated data bus, where the number of the memory ports is equal to the number of the network nodes.

1) The Shared Memory Communication Mechanism

The network nodes can communicate by leaving messages for one another (e.g., mailbox), or by process synchronization (e.g., critical region, and semaphores).

2) The Shared Memory System Characteristics

This is used as a communication tool as well as for the storage of data and programs. High transmission speed and high amounts of data are available when needed. This is quite a suitable system for the frequent transfer of a high volume of data between a central node and the other connected ones.

The main drawbacks with the shared memory are poor reliability, where there can be a system catastrophe if the shared memory fails. The expandability is a second problem, since it is limited by the number of ports. An example of this type of network is a Direct Numerical Control System (DNC), where a central computer includes a shared memory to load programs to each device, and provides communications between them, beside monitoring the whole system.

2. Ring or Loop Network

In this network type, nodes are attached to a cable so that it is shaped like a loop through the communication interfaces. The loop is a mono-direction ring bus, and all the nodes (e.g., computers, terminal, printer, sensors, etc.) are distributed related to each other, where each node is connected to two other nodes to form a closed loop. The loop can take the shape of star, but instead of a central switch, there is a switching box, which allows the addition and the removal of nodes from the network (e.g., IBM Token-ring).

1) The Ring Communication Mechanism

The communication here takes the form of exchanging messages. Message routing is achieved by two mechanisms. Central routing, where there is a control node in the loop which coordinates the message transmission, by only allowing one node to transmit a message at a time. The second mechanism is based on distributing the control among the network nodes by a "Token". Only the node which possesses the token can transmit its message.

The way of processing the message is easy, since the sender does not need to know the location of the receiver. Because all the messages follow one direction from one node to another node around the ring, each node recognizes its address will receive the message, copying it and send it to the next node, and so on.

2) The Ring Network Characteristics

This system is quite flexible for future network modifications and growth needs, where it is easy to plug any number of nodes within the system's capability into, or out of the operating network.

Redundancy is not expensive, since the prices for an extra cable and some connections are quite reasonable. This provides good reliability. The expandability is high, where each node in the ring network can be attached to another ring network, or to the plant backbone to provide unlimited communication facilities.

3. Shared Bus Network

A bus is a cable which extends through the whole system, with connection points. Nodes can be simply plugged in/out the network via standard interfaces any where on the bus. All the network nodes share access to the bus by an allocation scheme to provide facilities for the exchange of messages between them. Each node has its own local memory and consequently its own local addressing system. The bus may be parallel bus, where parallel wires each carry a data, address or control bit. Another alternative is a serial bus such as a twisted wire, a coaxial cable, or a fiber optics cable.

1) The Shared Bus Communication Mechanism

Each node in the network can send addressed messages to one or more nodes attached to the bus. The bus transmission routing can be controlled centrally or decentrally (distributed) as the ring networks, message routing can be controlled by a bus control node, or by a token. The control methods are quite different from those used in the ring networks.

2) The Shared Bus System Characteristics

The shared bus is the most flexible network system available. This has the same reliability as for the ring network and the same redundancy technique can be used. The network can be extended without problems.

4. Point-to-Point Network

In this type of network, each node is connected directly to all nodes through a dedicated single cable to each one. Each node has a fixed number of ports equal to N-1 on its communication interface, where N is the number of all micros or minis in the networ. This type is a complete interconnection system.

1) The Point-to-Point Communication Mechanism

Here, the communication occurs directly between the sender node and the receiver node, through the dedicated single cable between them. The sender node sends a request message through the connected link, which is dedicated to the concerned receiver, and waits for an acknowledgment, then starts to send its data messages or data packets.

2) The Point-to-Point System Characteristics

This system provides highest reliability, as a cable failure can be changed easily and quickly without a significant effect on the whole system. Transmission speed is relatively high (it depends on the capacity of the connected cable). The reliability of message transmission is high, where message loss is not assumed. Point-to-point network is not flexible to cope with changes and expansion needs. Beside the clumsy wiring system, which multiplies very rapidly relative to the number of nodes, where each node has N-1 cables, N is the number of nodes in the network. The network cost becomes prohibitive as the number of nodes and distances increase.

Today's research is to apply neutral network theory to underwater control system. With the technology, all the elements within the control system can communicate with each other freely and faster; higher reliability can also be archived.

2.3.11 Power conversion and distribution system

Any type of underwater equipment needs to have some sort of energy to operate it. For the underwater equipment we discussed so far, it is not possible to be operated by human power. The basis of our energy resource is electricity; it has form of AC and DC. The subsea end of energy source can be surface electricity, hydraulic, underwater generation or battery.

For complete underwater control system, one of the major work is to transfer power and signal. The commonly used power conversion systems are transformer, motor, hydraulic pump, switch, junction box, various gauges and meters.

The power requirements of ROV range from 1 to 200 kw for electrical and hydraulic, including any power requirement for inspection equipment or tools. Power is presently supplied via umbilical. Duration of operation is from 1 hour to several days, though individual missions maybe not longer than 8 hours.

The power requirements of Seabed vehicles arrange from 200 to 1500 kw for electrical and hydraulic, and are presently supplied via an umbilical. Duration of operation is from several days to several months continuously, with maintenance at periodic intervals.

1. Electricity as power resource

Most ROV systems are dependent on electric power from the generators of the support station. Units for internal power distribution to the control station, to the handling equipment and to the vehicle are normally included in the ROV systems.

- ROV with hydraulic propulsion systems and constant rotation electric thruster motors normally get three phases AC down the umbilical, suitable for direct powering of the electric motor in the electron-hydraulic aggregate. The rather high voltage three phases AC is normally also supplying power via onboard transformers to the rest of the vehicle sub systems.
- ROV with variable rotation electric thruster motors normally get DC power for each motor on separate conductors in the umbilical. In these cases electric power for the remaining sub systems is also provided with separate conductors.

The most common way of utilizing electricity is transmitte the eletricity from surface (normally generated from the ship generator) via umbilicals or cable. There are also cases the electricity is generated underwater, on the working system.

Most of the underwater equipments demand quite considerable amount of energy in order to accomplish their designated missions. Because of this nature, most of the system is chosen electricity as their primary energy source.

Remotely operated vehicles could benefit from local power sources such as fuel cells, stirling or diesel engines, though it is likely that an umbilical would still be required for control and instrumentation. As soon as the acoustic communication for such system has been developed to such a level that it can offer same or larger bandwidth as twisted-pair or coax cable, then the underwater equipment can be operated with a much large freedom.

Seabed vehicles require power above the power range which can be supplied by presently available or future developments of underwater power sources, though it should be possible to run several power sources in parallel to achieve the levels required.

A common requirement for all underwater robotic vehicles is a self-contained, high energy power system which can be installed with in a confined vehicle envelope. Many non-nuclear power system options have been considered, which can be broadly classified into two categories: electric power systems. Electric power systems have found wide use, in the form of silver oxide/zinc cells and Nickel Cadmium batteries. The Proton Exchange Membrane Technology is also being applied to develop compact fuel cells with increased underwater endurance. Thermal power system concepts are being studied for emerging robotic vehicles to obtain extended mission capability with the smallest possible vehicle envelope. These advances will accelerate the feasibility of low cost autonomous robots for long term underwater missions.

2. Hydraulic as power resource

Since all the underwater equipment we discussed here are mobile type, so transmission of power to the system becomes the most crucial problem. To solve this problem, researchers in many countries developed many different concepts, such as transmit electricity power directly from surface via special designed umbilcials, internal-combustion engine generation, fuel cells and batteries. Obviously, to transmit electricity directly from surface is the cheapest alternative. However, since some of the underwater vehicles need to move freely and travel not limited to the length of umbilicals, they have to have energy resource with them.

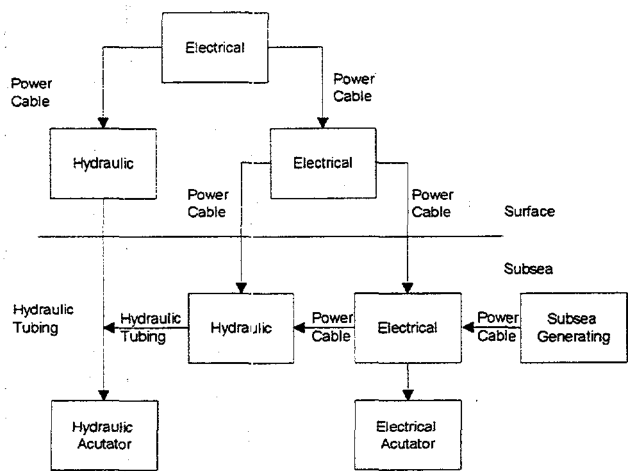


Figure 2.33 Power source and actuation power transfer

Because the compactness of hydraulic system, many of the underwater equipments have chosen hydraulic as the working energy form. A converting unit is introduced between actuator and electrical power system; this system is normally called Hydraulic Power Unit (HPU). This unit contains pumps, filters, reservoir(s), accumulators, valves, transducers and gauges. The HPU can be located at surface or at subsea. Figure 2.33 illustrates different concepts of energy transmission and application.

2.3.12 Test Stands and Test Equipment

Test stands and equipment are used to ensure that the control system equipment is functioning in accordance with all operational specification prior to installation. All the functions of the system are intensively tested before they go to offshore.

2.4 Control systems implementation and concept

2.4.1 Control system example for underwater submerisible

2.4.1.1 Typical control system for an AUV

A typical non-tethered, free swimming vehicle can deploy the following equipment (Figure 2.34):

- Obstacle Avoidance Sonar
- Still Cameras
- Gyrocompass
- TV Cameras
- Depth Sensor
- Flood & Strobe Lights

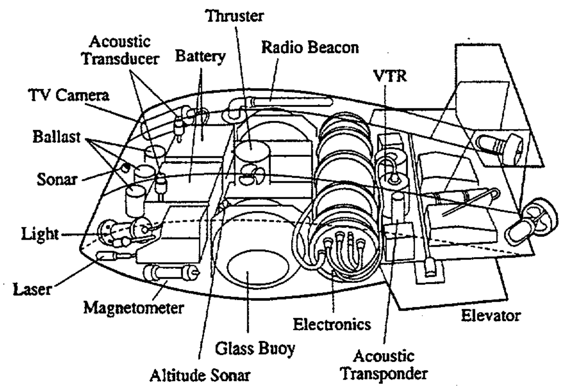


Figure 2.34 Arrangement of AE1000 (Kato, 95)

Untethered or autonomous ROVs currently use one of two propulsion strategies: battery powered or diesel powered.

These two types of propulsion systems each have distinctive advantages and disadvantages; however, each was designed under different criteria and each meets the requirement of its specific design task. Obviously in the future, the two propulsion subsystems, including hybrid battery-diesel configuration, will be used.

Untethered vehicles operate in one of two general modes:

- unsupervised (pre-programmed)

- supervised - acoustic control or radio control (RF).

In the unsupervised mode the mission is pre-programmed into the vehicle's microcomputer; heading, speed control, data collection and mission end (return) will be carried out without intervention from the surface. During the dive the vehicle may by means of acoustic link communicate with the operator, reporting vehicle status. Vehicle positioning is calculated by the use of a transponder array in which the surface interrogates the vehicle and the array and time delays are measured. This method of positioning is a standard, used throughout the underwater community.

The supervisory mode allows the vehicle to be manually controlled from the surface. The limitation on bandwidth and the slow rate at which data is transmitted through water requires the vehicle to have a high level of onboard intelligence for data collection and automatic obstacle avoidance. These two features are present in both the unsupervised and supervised modes.

The acoustic telemetry used for control in the supervised mode allows the operator to take over control of the vehicle or simply re-program the vehicle to carry out a new task.

The radio remote control vehicle allows for a vehicle to travel at high speed, 15 knots, while being quickly and accurately controlled from a mother vessel. The radio control (RF) vehicle also transmits real-time data, assuring the operator that the information collected is proper. The radio link travels over line of sight (approximately 10 km) and requires a surface antenna.

2.4.1.2 The TRITON ROV control system

The TRITON control system contains multiple processor, capable of automatic heading, pitch, roll, depth and altitude control, as well as operator adjustable control system gains which can be tuned to specific vehicle payloads, work packages, operating condition, and operator preferences. These functions are controlled with an Aerospace type joystick specially designed to minimize the pilot's workload. The TRITON ROV can also be configured from standard packages to achieve from 50 to 100 Hp in hydraulic capacity and from 1000 MSW to over 2500 MSW in depth capability.

1. Subsea control equipment

1) Mechanical protection - Canisters

In order to protect the electric and electronic device to the sea water, several protection canisters was implemented.

a) Instrument Power Canister

The instrument power canister contains the 1,200 VAC step-down transformer and regulated supplies at 120 VAC and 24 VDC along with dimmers for the vehicle lighting system, GFD Circuitry and subsystem isolation relays.

b) Control System canister

The control system contains the vehicle control and data telemetry system in a pressure vessel of the same design as the instrument power canister with access from both ends. This canister contains data transmission device, sensor interface, 2 microprocessor, closed loop controller, cooling fans, temperature sensor and alarm.

c) *Auxiliary Electronics Canister*

An auxiliary canister is provided on the vehicle to allow customers to and equipment which requires a one atmosphere housing. This canister has built-in access to vehicle power and control system with spare wires and capabilities, (both analog and digital), which are already mapped through the system and are tied in and accessed at the operator control console.

2) *Sensors*

Sensors are provided for automatic control of vehicle depth, altitude, heading, hydraulic pressure and hydraulic fluid temperature.

3) *Hydraulic Power System*

The Hydraulic Power Unit (HPU) on the TRITON system is 50 (100 hp optional). The vehicle and work package can each accommodate either an HPU of 25 hp or a dual 25 hp HPU to provide 50 hp capacity. The standard dual 25 horsepower HPUs provide redundancy, with either one capable of operating the vehicle with little decrease in vehicle performance.

4) *Sonar*

The standard TRITON sonar is a UDI A5360 high resolution short range scanning sonar: Forward Reverse Auto Scan.

5) *Camera and Light*

The standard TRITON vehicle camera is an Osprey Model 0E 1311 compact underwater television camera fitted with a 213" Vidicon tube. Totally self-contained, the camera operates on a low voltage DC power supply and the output video signal can be RF modulated for long line or high electrical interference environments. The built-in camera transformer handles up to five cameras.

Lights are six 250 watts ROS Ultralites. Lights are dimmed in pairs.

Still camera or video camera, can be installed on a Pan and Tilt unit to achieve the necessary maneuver. Pan can be operated in either a "slave" or a "rate" mode, allowing operator to hold pan angle with hands off joystick or allowing pan to automatically return to zero with hands off joystick. Tilt will always slave to joystick position.

2. Surface Control Equipment

1) *Control Console*

The control console is mounted in a standard 56 cm (22 in.) wide upright rack. A second 56 cm (22 in.) auxiliary rack is provided for additional equipment.

Information is displayed in two ways:

- 14 in. Graphic Monitor
- Video Annotation

(1) Graphic Display

IBM-PC facilitates modifications and expansions to handle how of work package data/displays. The Computer drawn gauges and meters display on the monitor toghther with compass repeater type display drawn on CRT with pan and tilt and artificial horizon.

Display items include:

- vehicle thrust displayed graphically
- vehicle beading; analog and digital
- tether payout
- hydraulic fluid temperature and pressure
- water intrusion
- pan and tilt angle
- CP probe readout
- control system status and gain adjust
- system alarm information
- vehicle turns
- vehicle attitude (pitch and roll)
- date and time
- diagnostic display and edit pages for operator intervention
- depth
- altitude
- telemetry status display
- still photo count
- light intensity bar graphs

(2) Pilot's Control Panel

The pilot's control panel, mounted at a 10' angle on the main rack unit' provides maximum operator comfort. The main joystick is a single aircraft-type used to control all six degrees-of-freedom of the vehicle. The functions are as follows (Table 2.5):

Table 2.5 Pilot's Control Function for Triton Vehicle

Controller Action	Corresponding Action from Vehicle
Push forward	Vehicle forward
Pull back	Vehicle reverses
Twist clockwise	Vehicle turns starboard
Twist counter clockwise	Vehicle turns port
Push left	Vehicle moves laterally to port
Push right	Vehicle moves laterally to starboard
Right thumb-switch forward	Vehicle pitches down forward
Right thumb-switch back	Vehicle pitches up forward

Controller Action	Corresponding Action from Vehicle
Right thumb-switch left	Vehicle rolls left
Right thumb-switch right	Vehicle rolls right
Left thumb-switch forward	Vehicle depth increases
Left thumb switch back	Vehicle depth decreases
Trigger	Still camera shutter/strobe release

In addition, tether pay-in and pay-out are controlled by a foot pedal and lights are controlled by panel mounted switches. Four potentiometers adjust thrust in surge, sway, yaw and heave direction. Pan and tilt controls are located on a separate two-axis joystick and arranged so that pan and tilt can be controlled with the left hand while the vehicle or manipulator is controlled with the right hand.

(3) Video Annotation

Data is annotated over the vehicle video display using the microprocessor system and the keyboard. Keyboard video annotation is included in the Control Housing processor.

Normal annotation will consist of:

- depth
- time
- date
- heading
- altitude
- pitch/roll
- pan and tilt

(4) Remote Console Unit (RCU)

The Pilot's Remote Console Unit (RCU) is 15cm (6 in.) high by 46cm (18 in.) wide by 30 cm (12 in.) deep and plugs in at the winch module. It is attached with a 15 m (50 ft.) cable. The RCU enables the pilot to operate the vehicle at distance from the control console when required for surface operation or maintenance.

The RCU has the main controls required for vehicle maneuvering:

- Two-axis joystick for surge and yaw and depth control
- Two-axis joystick for sway and depth
- Manual/auto heading control on-off
- Communications jack
- Tether in-out

(5) Power Distribution System

The power distribution system is comprised of two units: the Power Distribution Unit (PDU) and the Power Transformer Unit (KTU).

The PDU is located in the control van and houses all equipment required for monitoring and controlling power distribution.

- Voltage meters
- Current meters
- Elapsed time meters
- Manual breakers
- Overload protection
- Ground fault interrupt
- No high voltage in control van

(6) Power Transformer Unit (PTU)

The PTU contains the transformers and ground fault detection equipment for the standard 50 hp system. An additional PTU is added when up to 100 total horsepower is required for the vehicle or work package.

(7) Ground Fault Detection/Ground Fault Interrupt (GFD/GFI)

The ground fault detection system includes both detection and interrupt capability and operates equally well with both 110 volt and 2400 volt ac and all & voltage levels.

Ground Fault Detection/Ground Fault Interrupt features include:

- System monitoring by the ROV of power and light circuits
- Console monitoring of umbilical and tether power circuits
- Continuously operating sensing circuits for each power circuit
- Measurement of cable and connector systems for insulation resistance
- Measurement of jacket leakage resistance
- Measurement of leakage to sea water
- 1-15 megohm useful range
- Microprocessor controlled
- Each power circuit is checked 10 times per second
- Measurements are displayed on operator CRT for trend detection
- Audible and visual color coded arms
- Acknowledge or silence switch
- Power interrupted when two consecutive measurements are below trip level for very low false alarm rates
- Alarm and trip levels may be changed by use of editor feature
- Response time approximately 114 second
- Interrupt override switches

(8) Emergency Device

Pinger and Strobe are installed for the Emergency situations, such as power and pressure loss. The Pinger and Strobe will be activated while lost of power.

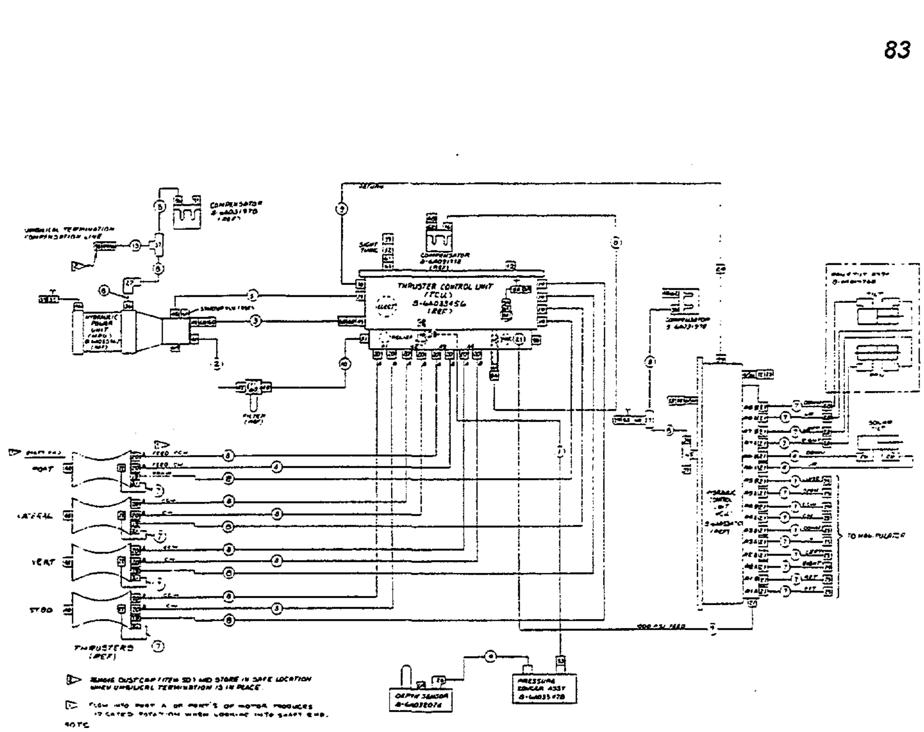


Figure 2.35 Typical Plumbing diagram of ROV (Courtesy by Stolt Nielsen a.s)

2.4.2 Underwater Manipulator control system

2.4.2.1 Type of control

The control of underwater manipulator has gained a lot of experience from its ancestor telemanipulator, which mainly used in nuclear industry. The control of them are almost the same, from the control method to control parameters.

The control system of manipulators is classified as following:

1. Open loop control

- On-Off control, each actuator is individually controlled by an on-off switch. Simultaneous joint motion may be possible to realize, but true joint coordination control is impossible.
- Proportional Joint-rate control, each actuator is individually controlled by a proportional controller, a potentiometer, for example. This control mode requires the operator to specify the velocity of each separate joint, and thus mentally transforms the coordinates of the task into arm-joint coordinates.
- Resolved motion rate control, each degree of freedom is individually control by a controller, it allows the operator to specify the velocity of the end effector. The commands are resolved into the remote axes mathematically. The interface for the human may be a button box (Figure 2.36) or joy stick. A button box still requires on operator action per coordinate axis, but the coordinated of the input can be made suitable for the human and the task being natural way. (As many as six have been

implemented.) Another approach to controlling 6 DOF is to use two joysticks or hand controllers, one for translation and one for rotation. Figure 2.36 is the standard button box for MAGNUM series manipulators.

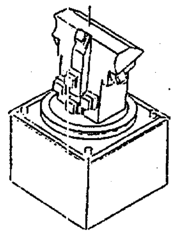


Figure 2.36 The button box for resolved motion rate control(Courtesy by Stolt Nielsen a.s)

2. Closed loop bilateral control

A complete bilateral manipulator system may have only one or up to all of its degree of freedom controlled bilaterally. On a typical manipulator system, each degree of freedom, or joints, are typically controlled independent of the operation of all other degree of freedom. The bilateral control is normally implementing the Master/Slave control. It should be noted that in a bilateral force reflection system, the distinction between "master" and "slave" is one of semantics, since the control system is symmetrical with respect to the master and slave. The master is usually the one closest to the operator.

- Spatially Correspondent, also called Position/position, each joint's position is controlled by master arm which is a kinematic replica of the slave manipulator. Movement of the Slave is caused by a computer activating servovalves based on feedback from position devices located at each manipulator function. Movement of the Master is directly mimicked by the Slave. Spatially correspondent manipulators are using the bilateral control to give the most efficient way in use, as they allow the operator to improve response time and increase work capability.

- Force reflection, also called Position/force, incorporates the features of simple master-slave control and in addition provides to the operator resistance to motions of the master unit that correspond to the resistance experienced by the slave unit. Sometimes the master and slave unit are identical except for the end effector. In other cases the master unit experiences reduced resistance to amplify the operator's strength and reduce his or her fatigue. This interface is also called bilateral master-slave control.

  Force reflection is a subset of force feedback. A force reflection system "feeds back" force the operator. This requires that the operator's interface device (typically a joystick or replica master arm) have some type of actuator to produce a suitable force in an appropriate axis. The operator's force signal may not be derived directly from forces acting on the slave.

  All telemanipulator systems indirectly have force feedback. If an operator tries to pass the manipulator through a solid object (for example, an offshore oil platform), the manipulator will fail to perform its tasks because moving to its commanded position would require application of a force that exceeds its physical limits. This force is "fed back" to the operator from the visual clue that motion has stopped. In this case, the force resolution of the manipulator system is directly related to the stiffness of the manipulator and to the object being manipulated.

2.4.2.2 Schilling TITAN 7F underwater manipulator

The Schilling underwater manipulator is a bilateral force reflection manipulator, it provides the operator with the ability to directly experience the motion and forces acting upon the slave arm by reflecting the forces to a replica Compact Master Control Arm. Force Reflection allows the operator to perform tasks in less time, with greater complexity (tasks that may be otherwise impossible without bilateral control), perform tasks without a special talent or long learning curves and reduce risk of damage to manipulator and work site.

1. Master control arm

The master control arm (MA) is constructed of impact resistant Delrin and is designed to be water resistant. The master arm utilizes a compact controller which fits comfortably in the palm of the operator's hand. The system can be configured for right or left hand operation. The control arm is a miniature replica of the slave arm with the same relative range of motion, it can be placed on almost any surface or can be hand held by the operator. The operator moves the master control arm with his wrist and fingers. Potentiometers in the joints of the master control arm allow the master controller electronics to determine the positioning of the master control arm.

2. The Controller System

The manipulator control system consists of a master unit and a slave unit designed around an Intel 8088 16-bit microprocessor. The position of the master control arm is measured and digitally transmitted to the slave unit fifty times per second, allowing smooth continuous operation.

The closed loop control of the manipulator is performed by the slave unit. Sophisticated linear and non linear digital control techniques are used to provide accurate positioning of the slave arm. Joint angles are measured one hundred times per second with a precision greater than one part in four thousand.

The controller electronics and the accompanying software perform all the sensory and decision making operations of the system. The controller consists of two 8088 microprocessors based boards, making up a master/slave board set. The boards are identical and their operation as master or slave is dependent only on the software booted upon startup. The subsea controller electronics becomes the slave unit and the master electronics becomes the master when the startup software checks which board is mounted. The master board has the capability to control more than one slave.

The master controller software generates the data used to update the tables in the slave control loop. This data is generated by either reading joint angle values from the master arm, or drawing this information from memory in the case of pre-programmed operation. Also contained in the master unit are the values which represent the limits of the operational envelope. These limits can be defined to prevent the manipulator from making unintended contact with other vehicle systems.

Communication between the Master and Slave is via a differential RS-422 serial link. This link is operated at 19.2K baud in a half-duplex mode resulting in a 9500 baud data transmission rate over a single twisted pair wire link. The slave controller monitors the positioning of the slave arm through potentiometers located within the hydraulic actuators that drive their functions. The slave controller then controls the servo valves to drive the hydraulic actuators until the position of the slave matches the position of the master arm.

3. The Slave Controller

The TITAN 7F slave electronics and power supply are housed in a one atmosphere enclosure. Vehicle interface is via a single 4 pin connector; two contacts for power and two for the data link. Hydraulic interface is made directly to the slave arm since the servo valves are incorporated in the slave arm itself.

4. Master arm with force reflection

The Force reflecting master arm (also called bilateral master arm, BMA) has the same overall size as the Master Arm without the force feedback option with the exception of the joints which are enlarged to accommodate the DC servo motors utilized to drive them. The motors at each joint of the BMA do not affect control of the system and operator interaction with the BMA is identical to the standard Master Arm. The Figure 2.37 shows the Dual arm configuration of Schilling compact master arm, and Figure 2.38 shows the structure and motion range of Schilling master arm.

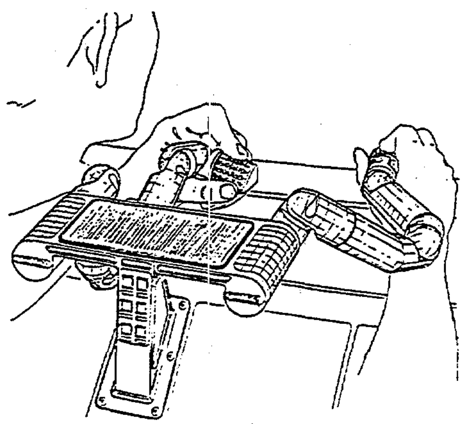


Figure 2.37 Schilling compact master arm (Dual arm)

The joints of the BMA are driven by DC servo motors , the jaw function is driven by a voice coil. The Bilateral Master Arm is much smaller in size than the classic force feedback master arm. This reduces the overall power requirements to actuate the Master Arm because of the lower moments and the mass of the arm. This has benefits in terms of power consumption and frequency response of the Master Arm itself.

The position and force sensing techniques are identical to the ones utilized in the slave arm. The commonality between sensing techniques and kinematic between Master and Slave Arm significantly reduces the system complexity by allowing very similar control techniques to be exercised at both hands of the system.

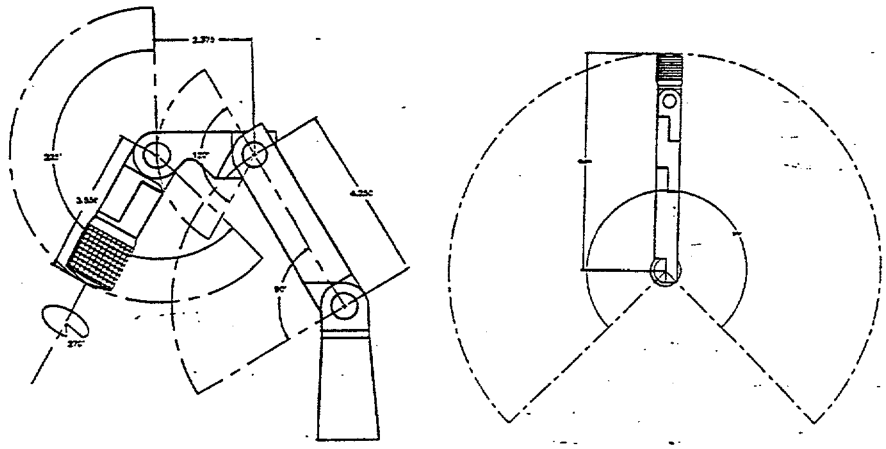


Figure 2.38 The working range of Schilling bilateral master arm

To make the Bilateral Master Arm as space efficient as possible, the motor position and force sensing devices are all integrated into a single module to reduce the overall volume impact on the Master Control Arm and it's working envelope.

5. Bilateral Control Units

There are two controllers; a Master Control Unit with the Bilateral Master Arm and a Slave Control Unit with the slave arm. The Master Control Unit has a set of servo drives of pulse width modulated design for running the motors in the Master control Arm. The Slave Control Unit uses similar circuitry as the standard TITAN 7F to run the servovalves.

These Control Units are based around a Texas Instruments digital signal processor Model TMS320C25 which operates at 40 MHz. The ultra high speed of this microprocessor allows Schilling Development to execute the control system in real-time. In addition, these processors allow the use of high power mathematics which is necessary to achieve the ultra high performance that Schilling Development has demonstrated with this bilateral control system.

6. The control mode for Schilling manipulator

1) The Master/Slave Control Loop

The master controller performs two operations. It gathers information from the front panel and master arm and then sends this information to the slave board upon request. The request comes in an information to the slave board upon request. The request comes in an information packet sent by the slave over the twisted pair. The position of the master arm is sensed by potentiometers within its joints, and their voltages are read by the master controller. In the Stow/Teach Mode, the master sends the position vectors from read-only memory rather than from the master arm. The master reads the options set with the keys on the front panel display. All of this information is then picketed and sent to the slave.

The slave software performs all the operations of the actual control loop of the system. The slave software first compares the present position of the slave arm is read from potentiometers as above. The slave software then increases the velocity vectors for the manipulator. The increments are selected based on the options set at the master. In normal master/slave operations, the increment is proportional to the difference between the positions or, if the difference is greater than a preset value, the maximum increment allowed by the program. The wrist rotation is either slaved, like the rest of the joints, or rate controlled by ignoring the position feedback. When the feedback is ignored, the software outputs a continuous velocity vector and the wrist rotates continuously at a rate proportional to the user input on the master.

The updated velocity vectors based on all these options are then sent to latching digital to analog converters on a rotating schedule. The first is a smoothing filter and buffer, and the second is a level shifter and gain amplifier that converts the -10) volt output of the DAC to the (10,-10) volt output required to drive the servo valves. If the slave receives no information for a period of time, indicating an abnormal interruption of communications, a watchdog circuit will reset the software to a waiting state, freezing all operations.

2) *Generalized Bilateral Manual control*

Bilateral manual control permits the operator to fell the forces and torques acting on the manipulator arm/hand while he manually controls the motion of the manipulator arm. In this control mode, the operator is kinematically and dynamically "coupled" to the remote manipulator arm and can command with "fell" and control with a "sense of touch". This type of man-machine coupling is an important element of "integrated operator control" in telemanipulation.

2.4.3 Control system used in ROT (Typical)

A typical control system for a ROT (remote operated tool) is normally consists following functions (Figure 2.41):

- Linear actuator(hydraulic cylinder)
- Rotatory actuator (hydraulic rotatory cylinder or motor)
- Sensors
- Power/signal conversion equipment

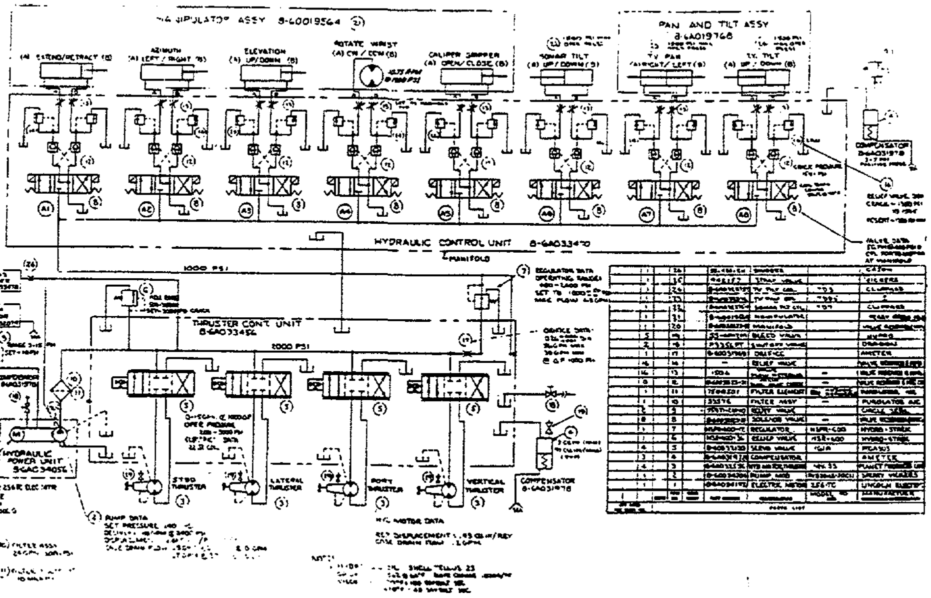


Figure 2.39 Typical hydraulic diagram of ROV

2.4.3.1 Example of ROT control system

The TOGI tool package was designed and made for Norsk Hydro by Oceanring for TOGI field, it consists a hydraulic skid and a suite of tools. The hydraulic power supply skid is used to provide hydraulic power and control, the suite of tools developed for operations and override of various functions on the TOGI template. The tools are either attached to the skid front to “fly in” or put in a tool basket.

Hydraulic supply to the skid hydraulic circuit is taken from the host ROV's hydraulics via 2 x 1” 3000 psi rated hoses. This supply is run through a master on/off valve to the motor of a motor/pump combination. The pump of the motor/pump combination unit supplies the skid circuit with hydraulic power. Hydraulic fluid is filtered prior to entering the manifold block of the rate valve pack where it is distributed to the proportional pressure reducing valve. The 8 solenoid valves in the rate valve pack are fed from the proportional pressure reducing valve and control the functions of the tooling packages via a Q.D manifold plate. Hydraulic pressure from the proportional pressure reducing valve is controlled via the telemetry system to suit circuit application.

Control of the hydraulic power supply skid functions and display of system status is provided by the control console. A spare twisted pair conductor in the host ROV's umbilical is used to establish a telemetry link between the control console and skid. Both the skid and console are supplied with power from the host ROV's telemetry can and console respectively. By supplying power and telemetry links to the skid and console in this manner, the number of electrical interfaces is reduced to a minimum while integrating the skid with the emergency power shut down system of the host ROV.

1. Skid Hydraulic Supply

The skid derives its hydraulic supply from the host ROV. 2 x 1" JIC male connectors are situated at the rear of the Skid. 2 x 1" 3000 psi hoses labeled 'supply' and 'return' are provided for connection to the host ROV.

2. Telemetry/Electrical

1) Console Electrical Supply/Telemetry Interface

The console acts as the interface between the operator and the telemetry. It allows the operator to control specific valves, set the system hydraulic pressure by way of the Rexroth proportional pressure reducing valve, keep track of tool rotations, oil reservoir level etc. Control of the skid functions is implemented by a spare shielded twisted pair run down the host ROV's umbilical.

Table 2.6 Technical information of TOGI control system

FUNCTION NAME	TYPE	OPERATIONAL MODE	COMMENT
Console power	Latched Switch(green)	All	Provides power to the console electronics
Skid Power	Lamp (green)	All	Indicates that skid has electronic power and that there is a working telemetry link when not illuminated. Note that if the lamp is illuminated there may be no power at the skid or there may not be a working telemetry link.
Skid Hyd. On/Off	Momentary with latch on (green) off (red)	All	Skid hyd. power on/off-hyd. off can be activated by the reservoir empty alarm or pressure alarm.
Skid Hyd. pressure	LED readout 0-3500 psi	All	Constant readout of skid hyd. pressure.
Main Oil Level	Analog mtr.	All	Constant readings on main oil reservoir.
Interlock Override	Momentary with latch (red)	All	Provides a means of overriding an alarm condition. Note: conditions are over pressure (torque mode) and main reservoir empty.
Torque Tool	Momentary	Torque tool	Enables torque tool

FUNCTION NAME	TYPE	OPERATIONAL MODE	COMMENT
(Mode select)	latch(yellow)		section of console.
Torque command (6 levels)	Momentary latch (yellow)	Torque tool	Outputs a fixed voltage value to the R133 card which in turn controls the Rexroth pressure reducing valve, outputting a fixed hyd. pressure. This value is controlled by the setting of potentiometers Pl-P6 on the back of the console. Selection of a torque command level is only possible by prior selection of an immediately adjacent torque command level. Selection of the torque tool mode automatically enables torque command level I.
Rotations CW/ CCW	Momentary(yellow)	Torque tool	Operates the torque tool valve in CW direction and CCW direction.
Torque settings	LED readout	Torque tool	Meter readout can be adjusted to read anything from 0-8888 ftlbs controlled by potentiometers PM1-PM6 on the back of the console.
Tool rotations	LED readout	Torque tool	Counts number of 1 rotations made by tool. Counts up CW. Counts down CCW.
Tool pressure alarm	Lamp (red)	Torque tool	Indicates actual pressure is higher than command pressure(fault condition). Pressure alarm will reset torque command buttons and turn off skid hydraulics. It can be overridden by the interlock override button.

FUNCTION NAME	TYPE	OPERATIONAL MODE	COMMENT
Spare Valve	Momentary(yellow)	Torque tool	Operates spare valve.
Hot Stab(mode select)	Momentary latch (ORG)	All	Enables hot stab section of the console.
Hot stab extend/retract	Momentary(ORG)	Hot stab	Extends and retracts hot stab tool
Pressure up	Momentary(ORG)	Hot stab	Allow system pressure to hot stab tool.
Main/Alt	Toggle switch	Hot stab	Selects which port of Hot Stab Tool to pressure up.
Dump to Sea	Momentary(ORG)	Hot Stab	Allows oil to flow from skid, through tool, through subsea equipment, back through skid and out to sea. Flow direction set by Main/Alt switch.
Grease Gun	Momentary(ORG)	Hot stab	Allows system pressure to Grease gun tool.
Spare Valve	Momentary(ORG)	Hot stab	Operates spare valve.
Pressure adjust	Pot	Hot stab, motor override	Allows adjustment for system pressure from 170 psi to full. Operates only in hot stab on motor override modes
Motor override (Mode Select)	Momentary latch (Green)	All	Enables the motor override section of the console.
Motor override extend/retract	Momentary(Green)	Motor override	Extends and retracts motor override tool (Hot Line Stab).
Motor override Rotate CW/CCW	Momentary(Green)	Motor override	Allows system pressure to motor override tool to actuate motor in CW or CCW direction.
Spare	Momentary	Motor(Green)	Spare buttons only, not wired to a valve override

The interface between the console front panel and the telemetry system are the three switch logic cards:

a) *Logic card A:*
contains the torque command button logic and comparator for the pressure alarm.

b) *Logic card B:*

contains solid state latches, which allow for mode selection.

c) *Logic card C:*

contains additional solid state latches, mode select circuitry and pressure alarm selection logic.

2.4.3.2 RMS Telemetry General Description

The TOGI telemetry control system is based around the RMS T204 card set as used on the ISE Hydra ROV's.

The TOGI skid telemetry system is a half duplex system transmitting three groups of serial data from the console to the skid and two groups of data from the skid back up to the console. This data is used by the system both for transferring information between the console and skid as well as effecting control over the various tools that will be powered and controlled by the skid.

The TOGI telemetry system is based around the T204C card which generates the main timing signals and encodes/decodes the data. The timing signals generated by the T204C are used by the other system boards to transmit or receive data. The console T204C card is configured as the system master and the skid T204C is the slave. The master T2O4C card will provide a synchronization pulse to the slave along with the data. The slave will not operate without first receiving a sync pulse and data from the master.

The data transmission is in a RS422 biphase NRZ format and the data stream is configured as five groups of sixteen words, each word containing eight bits.

1) RMS Telemetry Detailed Description : T2O4-C

The T204C produces all the timing and control signals necessary for a half duplex telemetry system. Most of the integrated circuits used are CMOS enabling low power consumption and a wide operating temperature range.

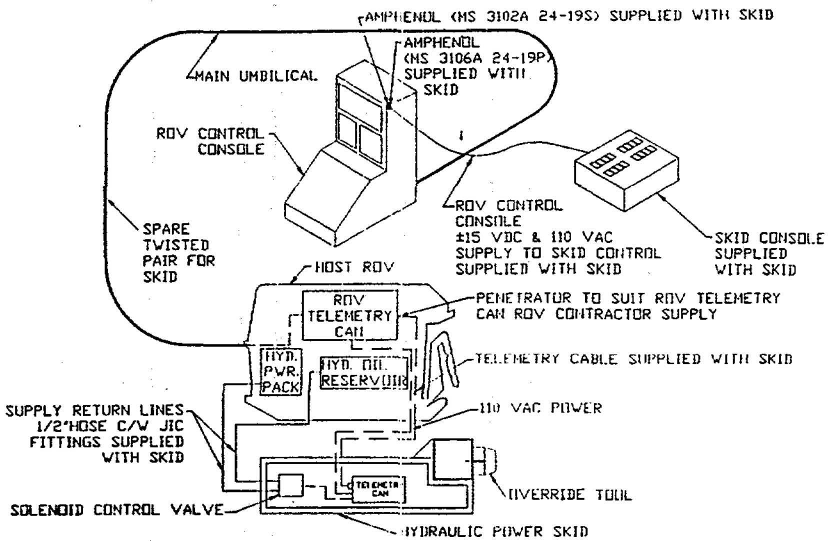


Figure 2.40 TOGI ROV tooling system interface diagram

Some features of the T2O4C are:

- High current balanced line drivers (R5422) Optically isolated input and output Selectable bit rate Crystal controlled clock Data transmitted with biphase L encoding

The board can be divided into two main areas:

1. Receiver/transmitter
2. Sync and timing

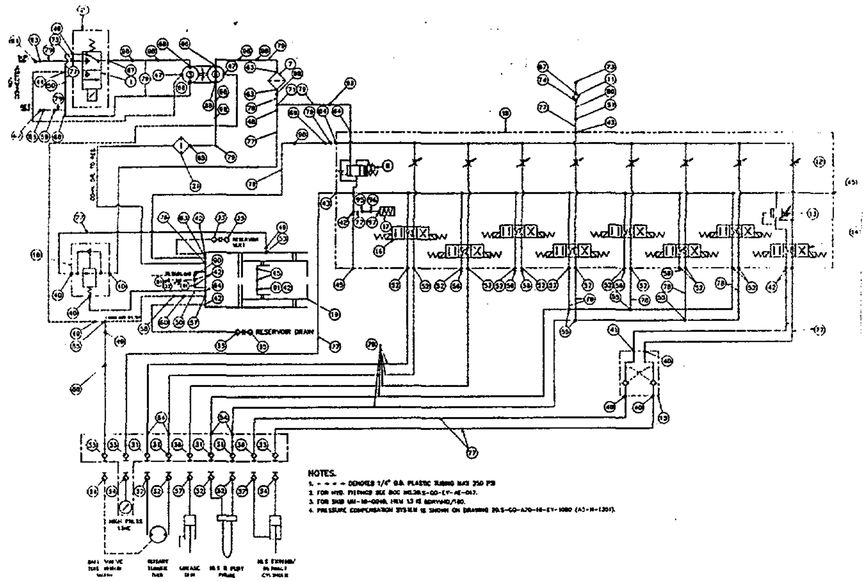


Figure 2.41 TOGI ROV tooling hydraulic system

3 Design method for underwater control system

3.1 Theory of design methods

To design a new product, or a new system, can be viewed as a problem-solving process. Because design has a crucial effect on the technical and economical value of the product, production methods can only be optimized within the established framework of product design.

Meeting the requirements of a product specification is accomplished most easily if design engineers have a set of guidelines that are established initially in the program and can follow through each step of the design process. This ensures that all aspects of the specification are considered as an integral part of the design process rather than as an after thought. These guidelines are normally prepared as design criteria that provide detailed identification of all the points that each design engineer should consider as the design evolves.

Ullman (92) defined that design method is "a procedure enables the designer follows a certain system to solve the problem. At the end, the designer must be taught, or be expected to learn, all the special skills underlying systematic thought and procedure".

Well defined procedure will lead the designer to find possible solutions more quickly and directly than any other. As other disciplines become more scientific, and as the logical data preparation increasingly use computer, so designing, too, must become more logical, more sequential, more transparent, and more open to correction.

This is not meant to detract from the importance of intuition or experience, any logical and systemic approach involves a measure of intuition of the overall solution.

Systematic design alone can produce a truly rational approach and hence generally valid solutions, that is, solutions that can be used time and again. It also helps to establish a workable schedule based on rational project planning, such as Critical Path Analysis, and hence enables the designer to predict how much time he will have to spend on a feasibility study, how much on the search on similarity laws, so useful in model testing, along with consistent use of standard specifications, size ranges and modular methods, facilitates further rationalization, not only in the design activity, but throughout the entire production process.

3.1.1 Definition of Design methods

A design method must have the following characteristics: It must

- encourage a problem-directed approach; that is, it must be applicable to different type of design activity;
- foster inventiveness and understanding; that is, facilitate the search for optimum solutions;
- be compatible with the concepts, methods and findings of other disciplines;
- not rely on chance;

- facilitate the application of known solutions to related tasks;
- be compatible with electronic data processing;
- be easily taught and learned; and
- reflect modern management-science thinking; that is to reduce workload, save time, prevent human error and help to maintain active interest.

A common design approach consists of the following steps: definition of the problem, collection of data, analysis of data, development of alternatives, and selection and implementation of the solution. The process is of an iterative character; one has to move back and forth, collect more information, analyze a new, redefine the problem, modify previous conclusions, and so on.

The following sections of this chapter are going through the most important steps and review and define some guideline which will be essential to a design process.

3.1.2 Design process

Developing a product from an initial need to a final prototype is not an easy job. The process is different from product to product and industry to industry, but we can construct a generic diagram of the product design process (Figure 3.1). The first three phases in a product's life cycle are: specification development/planning, conceptual design, and product design. The other parts in the same cycle such as product manufacturing, marketing, service and retirement of the product, are not the concern of this chapter.

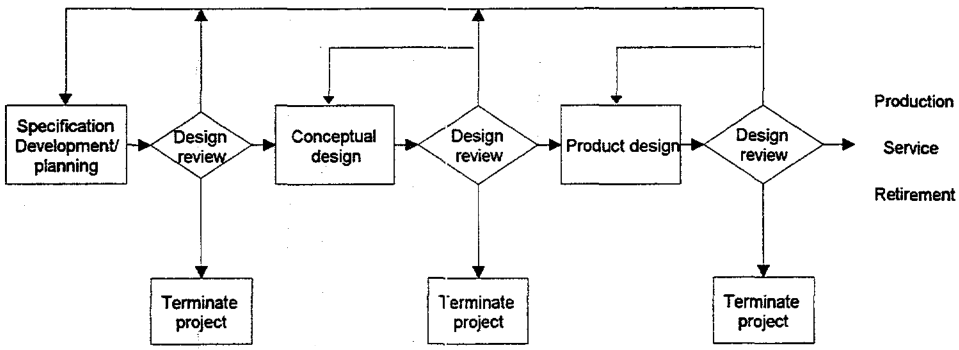


Figure 3.1 Phases in a design process

Before the design of a product can begin, the need for that item must be established. The need can have three sources: the market, the development of a new technology, or the need from a higher-level system. Most product design is essentially market-driven; without a customer for the product, there will be no way to recover the costs of design and manufacture. The most important part in understanding the design problem lies in assessing the market, in establishing what the customer wants in the product.

Often a company will want to develop a product utilizing a new technology. Developing new technologies usually requires an extensive amount of capital investment and possibly years of scientific and engineering time. These types of products are very risky financially, but they may obtain a large profit because of their uniqueness.

Besides totally new product development, the need for a new product can also come from the decomposition of a higher-level system. Such system normally consists many sub-systems; with the needs of new development or refinement of the general system, the sub-system development will follow as a new development. For example, development of a new control unit for an underwater equipment could come from decomposition of a new underwater equipment development project.

3.1.2.1 Main phases in a product development

A product development consists three main phases, specification development/planning phase, conceptual design phase and product design phase.

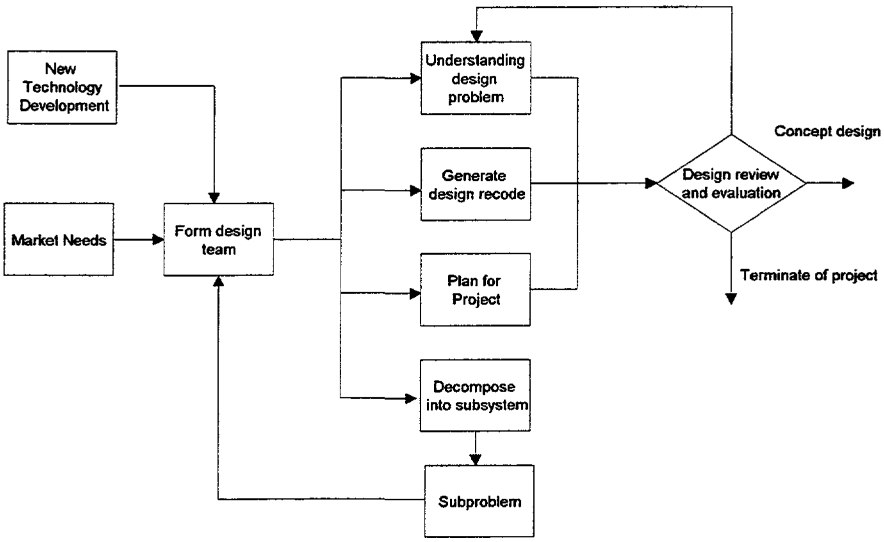


Figure 3.2 Specification definition phase

1. Specification Development/Planning phase

During the specification development/planning phase, the goal is to understand the problem and lay the foundation for the remainder of the design project. For most projects of any size, the first step is forming the *design team*. Very few products or even subsystems are designed by one person.

In this phase (Figure 3.2) the design team must accomplish two main tasks: *understand the design problem* and *plan for the design*. Understanding the problem may seem to be a simple task, but, experience shows most design problems are ill-defined initially, finding out exactly what the customer really wants can be a major undertaking. We will look at a technique to accomplish this later in the chapter. These customer's requirements are then used as a basis for assessing the competition and for generating engineering requirements or specifications, measurable behaviors of the product-to-be. The defined design problem that will help, later in the design process, to determine the product's quality.

Once the design team understands the problem, they must establish a plan for executing the remainder of the design process. The plan must have a clear strategy for proceeding to production; it must give estimates for the time, personnel requirements, and costs of following the plan.

At the end of this phase of the design process, as in all the others, there is a *design review*, a formal meeting where the members of the design team report their progress to management. Depending on the results of the design review, management will decide either to continue the development of the product or to terminate the project before any more resources are spent. Often, the results of specification development will determine how the design problem can be decomposed into smaller, more manageable design sub-problems.

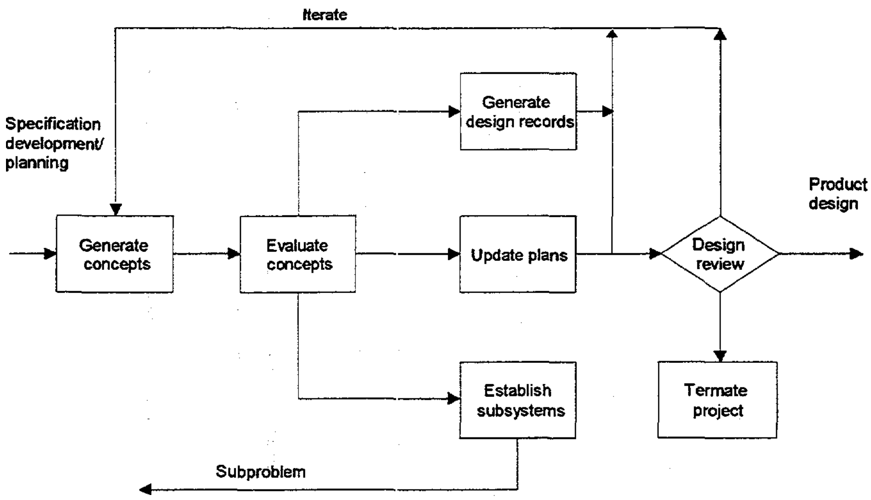


Figure 3.3 Concept generating Phase

2. Conceptual Design phase

The designers use the results of the specification development/planning phase to generate and evaluate concepts for the product. During *concept generation,* the customer's requirements serve as a basis for developing a functional model of the design. Employing a technique that makes it possible to determine how the product will function, with as yet minimum commitment to any specific configuration. The understanding gained through this functional approach is essential for developing conceptual designs that lead to a quality product.

During *concept evaluation* the goal is to compare the concepts generated to the requirements developed during specification development and to select the best concept(s) for refinement into products.

Techniques for generating and evaluating concepts are used iteratively. As design concepts are evaluated, more ideas are generated and need to be evaluated. Because iteration is less expensive during this phase than in the product design phase, it should be encouraged here, before the product is developed into too much detail.

As a result of knowledge gained during conceptual design phase, the problem is often broken into more manageable subsystems for individual design efforts. Thus, what began as a single design problem may now be many subproblems, and the concepts generated for each sub-problem need to be developed into manufacturable products.

The introduce of small and more manageable sub-problem has great advantage than solving overall problem as one piece; however, the need for interface coordination must be strongly emphasized. The interface problem is not just exist between the general problem and sub-problems; it also exists between sub-problems. In order to reduce the complexity of the problem, the sub-problems are developed under the assumption of independent to each other, which is normally not the case; many of the sub-problems have their own built in interface. With lack of interface coordination between sub-problems, problem might arise because of the incompatibility.

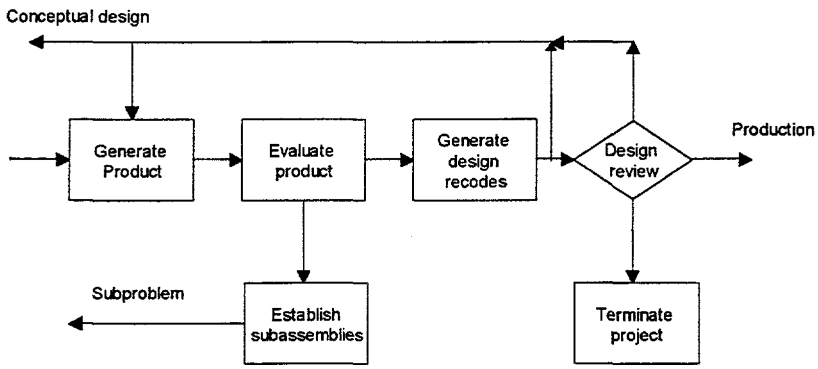


Figure 3.4 Product design phase

3. Product Design phase

After concepts have been generated and evaluated, it is time to refine the best of them into actual products. The conceptual design phase leads to *product generation.* Techniques for generating product designs, emphasize the importance of the concurrent design of the product and the manufacturing process. As the product designs are generated, they are evaluated; and as the product is increasingly refined, more evaluation methods become available. As shown in Figure 3.4, product generation and evaluation are synergistic, they form an iterative loop. The evaluation of proposed components and assemblies leads naturally to their generation and improvement. Evaluation can also shunt the design process back to the conceptual phase. The product design phase concludes with the need to finalize the product.

3.1.2.2 Techniques used in design process

The techniques used in the design process are listed as following. However, each design problem is different and some of the techniques may not be applicable to some problems. So when the design engineers use the following techniques, they have to use discretion in selecting the best technique for each situation.

1. Specification Development/Planning Phase

- Understanding the design problem
- Assessing customer requirements
- Assessing the competition
- Generating engineering specification and border conditions
- Establishing engineering targets
- Planning for design

2. Conceptual Design Phase

- Generating concepts
- Functional decomposition
- Generating concepts from functions
- Considering product and production concept concurrently
- Evaluating concepts
    - Judging feasibility
    - Assessing technology readiness
    - Go/no-go screening
    - Using the decision matrix

3. Product Design Phase

- Generating the product
- Transforming existing products
- Embodying the functions
- Designing product and production concurrently
- Patching and refining the product
- Evaluating the product
    - Monitoring functional changes
    - Evaluating performance
        - Using experimental models
        - Using analytical models
- Optimizing design
- Using robust design
- Evaluating costs
    - Designing for assembly
    - Designing for the other "Utilities"
- Finalizing the product

To apply design process does not mean that we have to scrap everything we had from before but to give a chance to reconsider the product's design based on the experience we obtained from previous design.

The goal of the design process is not to eliminate changes but to manage the evolution of the design so that most changes come through iterations early in the process.

The techniques listed also help in developing creative solutions to design problems. The techniques also force documentation of the progress of the design, requiring the development of informational tables and matrices, records of the design's evolution that will be useful in many ways.

To apply the techniques can cause frustration. In normal practice, in trying to understand a new problem, we will certainly develop a potential solution. Our tendency then is to concentrate on this solution and develop it into a manufacturable product, even though the solution may not be a very good one. In order to acting against the desire to refine our first idea, the techniques force us to consider many other potentially better solutions.

3.1.2.3 Sources for concept ideas

To be able to find ideas for a new product, it is important that there are enough information can help to understand the problem and generate ideas. The following in this section is a list of useful sources of information for designs that might keep a designer from reinventing the wheel. Unfortunately, a majority of these sources refer to products that are already embodied as form, which can influence the concepts generated.

1. Using Patents

Although the patent literature is a good source of ideas, there are problems in its use. First, it is hard to find what you want in the literature. Second, it is easy to find other, interesting, distracting things not related to the problem at hand. Third, patents are difficult to read.

There are millions of patents, each with many diagrams and each having diverse claims. To call these to a reasonable number, a *patent search* must be performed. That is, all the patents that relate to a certain idea must be found. This can be done by any individual, but it is best accomplished by a professional familiar with the literature.

2. Reference Books and Trade Journals

Most reference books give analytical techniques that are not very useful in the early stages of a design project, but in some of them you will find a few abstract ideas that are useful at this stage-usually in design areas that are quite mature and usually ideas so decomposed that their form has specific function.

Many good ideas are published in trade journals, which are usually oriented towards a specific discipline. Some, however, are targeted at designers and thus contain information from many fields.

3. Using Experts to Help Generate Concepts

If designing in a new domain, one in which we are not experienced, we have two choices in how to gain the knowledge sufficient to generate concepts. We either find someone with expertise in that domain or spend time gaining experience on our own.

A good source of information is manufacturers' catalogs and, even better, manufacturers' representatives. A good designer usually spends a great deal of time with these representatives, trying to find sources for specific items or trying to find "another way to do it."

4. Brainstorming as a Source of Ideas

Brainstorming was initially developed as group-oriented technique, but it can also be used by an individual designer. What makes brainstorming especially good for group efforts is that each member of the group can contribute ideas from his or her own viewpoint. Essentially, the rules for brainstorming are quite simple:

1. Think wild.
2. Record all the ideas generated.
3. Generate as many ideas as possible, then verbalize these ideas.
4. Do not evaluate the ideas; just generate them. In a group situation, do not allow criticism of others' ideas.

Brainstorming sessions should be focused on one specific function.

3.1.3 Applying design method to a design problem

In order to apply the design method to a design problem, more detailed steps and necessary guideline should also be defined. The following sections are trying to outline such steps and guidelines.

3.1.3.1 The specification development/planning phase

The structure of this first phase is shown in Figure 3.2. The first activity is forming the design team. The team's main activities then become understanding the design problem and planning for the remainder of the project. Often, when working to understand and develop a clear set of requirements for the problem, the design team will realize that it can be decomposed into a set of loosely related sub-problems, each of which may be treated as an individual design problem. Additionally in applying the design techniques, the team will generating design records, which will become part of the documentation of the project.

1. Understanding the design problem

In order to have an understanding of the customer requirements, many techniques were developed, such as QFD method, conjoint analysis, etc. (Gustafsson, 93). In the following sections we will introduce the QFD method and apply it later in this chapter.

1) The Quality Function Deployment (QFD) Technique

Quality Function Deployment, or the QFD method, was developed in Japan in the mid-1970s and introduced in United States in the late 1980s. This method came to Nordic country in end of 1980s. Using this method, Toyota was able to reduce the costs of bringing a new car model to market by over 60 percent and to decrease the time required for its development by one-third. They achieved results while improving the quality of the product. Many U.S. companies now use the QFD method regularly projects and first QFD software packages became available in U.S. around 1989 (Ullman, 92, Cohen, 95).

One of the definition of QFD was given by Slabey that is stated that QFD is: "A system for translating consumer requirements into appropriate company requirements at each stage from research and product development to engineering and manufacturing to marketing/sales and distribution". In other words it is a process that makes sure that the customer receives what he wants (Gustafsson, 93). As described below, this method involved a time commitment, but its effectiveness dictates that it be followed from the beginning of all design.

QFD provides a standardized method of representing customer needs. This method is by no means a method of learning what the customer needs are, but it does provide a way of systematically representing those needs. The standard representation can then be used as a basis for itemizing differences of opinion, which can be researched as needed.

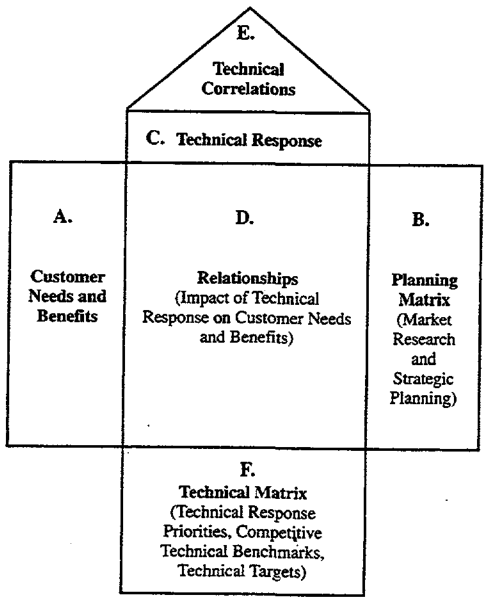


Figure 3.5 The House of Quality

The QFD process involves constructing matrices (sometimes called "quality tables"). The first of these matrices is called the "House of Quality" (HOQ). The matrix consists of several sections or sub-matrices joined together in various ways, each containing information related to the others (Figure 3.5). A Classical QFD Model shows the relationship between the various matrices (Table 3.1), Figure 3.6 and illustrates this classical model.

Table 3.1 Classical Model for QFD (Cohen, 95)

Matrix	What	How
House of Quality	Voice of the Customer	Technical Performance Measures
Subsystem Design Matrix	Technical performance measures	Piece-Part Characteristics
Piece Part design matrix	Piece-part Characteristics	Process Parameters
Process Design	Matrix Process Parameters	Production Operation

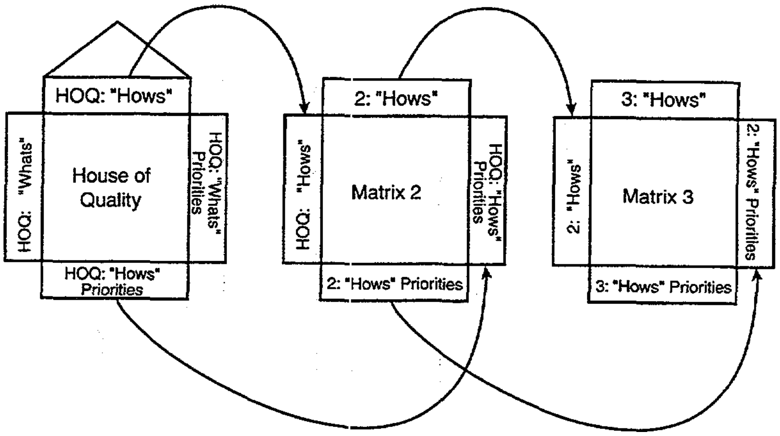


Figure 3.6 Interrelated Matrices

The steps presented below are illustrated in the form and flow diagram shown in Figure 3.7 and Figure 3.8. This form serves as a guide to translating customer requirement to firm engineering targets.

STEP 1: Identifying the customer(s).

The goal in understanding the design problem is to translate customer requirements into a technical description of what needs to be designed. To do this, we must first determine exactly who the customer is. For most design situations there is more than one customer; for many products the most important customer is the consumer. For the underwater equipment which is not a consumer product, we have a very limited customer base.

STEP 2. Determining customer requirements.

Once the customers have been identified, the next goal of the QFD method is to determine what is to be designed. That is, what is it that the customer wants? Depending on the customer, we can outline some typical requirements.

Our goal here is to develop a list of all the requirements that will affect the design. As it is important that all views be taken into account, this procedure should be accomplished with the whole design team and should be based on the results of customer surveys. The desires of the customer are obtained mainly through interviews and questionnaires.

A list of customer requirements could be made in the customers own words such as "easy," "fast," "natural," and other abstract terms. A later step in the design process will be to translate these terms into engineering parameters. However, designers and customers should have the same idea about the ranges of those abstract terms. Whenever it is possible, quantifying of the relative requirements (with reference to the abstract terms by customer) should be done as early as possible to avoid unnecessary misunderstanding.

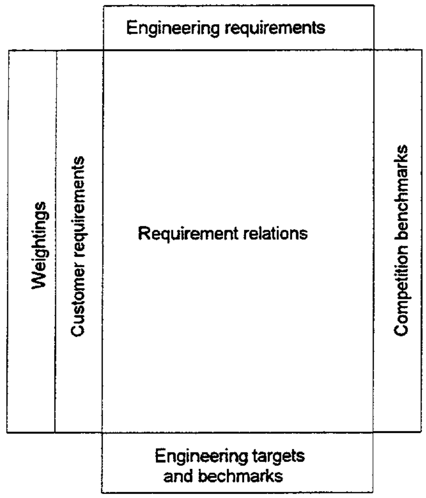


Figure 3.7 The problem understanding form

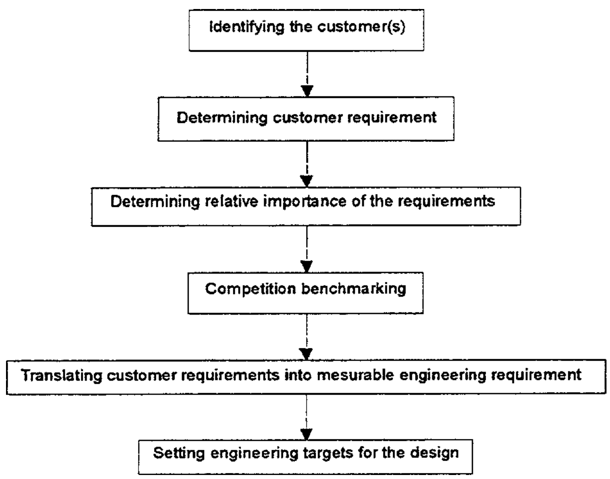


Figure 3.8 Steps in QFD process

Collecting and assessing for such information is an iterative effort; the goal is to develop a complete list. One way to ensure that is to organize the list by types of requirements. The major types are shown as follows (Ullman, 92)

(1) Performance

- Functional performance

- Spatial constraints

a Appearance
b Time
c Cost
- Capital
- Unit

d Manufacture/assembly
- Quantity to be manufactured
- Company capabilities

e Standards
f Safety
g Environmental issues

Performance and *appearance* are of primary importance to the consumer. Performance requirements can be roughly divided into those concerning the design's function and the spatial constraints on it.

Functional performance requirements are those elements of the performance that describe the product's behavior; its human interface; its environmental operating conditions; its aging properties; and its failure and repair possibilities. *Spatial constraints* are the performance requirements that relate to how the product must fit with other, or existing objects. The actual look of the design is considered an appearance requirement.

Cost requirements concern both the capital costs and costs per unit of production. Included in capital costs are expenditures for the design of the product.

Some of the *manufacturing/assembly requirements* are dictated by the quantity of the design to be produced and the characteristics of the company producing the design. The quantity to be produced often affects the kind of manufacturing processes to be used. Such factors must be considered from the very beginning.

Standards are the guidelines in current engineering practice in common design situations.

Last but not least, in today's more restricted requirement for environment; the design engineer needs to list requirements imposed by *environmental concerns.* Since the design process must consider the entire life cycle of the product, it is the design engineer's responsibility to establish the impact of the product on the environment during production, operation, and retirement.

STEP 3: Determining relative importance of the requirements

The next step in the QFD technique is to evaluate the importance of each of the customer requirements. This is accomplished by generating a weighting factor for each requirement and entering it in Figure 3.7. The weighting will give an idea of how much effort, time, and money to invest in achieving each requirement.

Some requirements in the list are absolute *must.* These *must* requirements could be determined by the nature of the product or basic requirement of the user. If they are not met, the design is useless or not able to be accepted by the customer. Such requirements are usually associated with standards, spatial, or company requirements. However, care must be taken in identifying these *musts*; not all requirements are essential; too many *must* may limit the possible solution of a design.

The requirements that remain after identifying the *must* requirements are considered as *wants;* these *wants* can be formed by the desire of high-end function from the user or by considering some factors in manufacturing. They must be weighted according to relative importance. To determine importance, a pairwise comparison technique is often used.

To be able to determine which of requirements is must or want requires a lot of competence and insight from the designer. Experts and other help may be used for such task.

STEP 4: Competition benchmarking.

The goal here is to determine how the customer perceives the competition's ability to meet each of the requirements. The purpose for doing this was two folds: First, it forces an awareness of what already existed, and, second, it points out opportunities to improve on what already exists.

In some companies this process is called *competition benchmarking* and is a major aspect of understanding a design problem. In benchmarking, each competing product must be compared with customer requirements. Some of these comparisons are objective and can be measured directly; others are subjective and customer opinion may be needed. An example given by Ullman introduced a benchmarking rating of the existing design on a scale of 1 to 5. For each customer requirement, where

1 = the design does not meet the requirement at all.
2 = the design meets the requirement slightly.
3 = the design meets the requirement somewhat.
4 = the design meets the requirement mostly.
5 = the design fulfills the requirement completely.

These ratings are mainly for illustration purpose, for each specify performance parameter, the rating should be defined as needed. Though these are not very refined ratings, they do give an indication of how the competition is perceived by the customer, we will look at the competition again in step 6 of the QFD technique.

STEP 5: Translating customer requirements into measurable engineering requirements.

The goal here is to develop a set of engineering requirements (often called design specifications) that are measurable for use in evaluating proposed product designs. First, we need to transform from *customer requirements* to *engineering requirements.* Second, we need to make sure that each engineering requirement is *measurable.* Some customer requirements are directly measurable; this step does not apply to them.

We begin by finding as many engineering requirements as possible that indicate a level of achievement for each customer requirement.

An important point here is that every effort needs to be made to find as many ways as possible to measure each customer requirement. If there are no measurable engineering requirements for a specific customer requirement, then there is a problem. This is usually an indication that the customer requirement is not well understood. Possible solutions are to break the requirement into finer independent parts or to redo step 3, with specific attention to that specific requirement.

To complete this step, we fill in the center portion of the Problem Understanding Form (Figure 3.7). Each cell of the form represents how each engineering requirement relates to each customer requirement. The strength of this relationship can vary, with some engineering requirements providing strong measures for a customer's requirement and others providing no measure at all. This relation will be conveyed through numerical values. Ullman uses the following four values as the relationship indication (92):

9 = strong relation
3 = medium relation
1 = weak relation
Blank = no relation at all

STEP 6: Setting engineering targets for the design.

The last step in the QFD technique is to determine target values for each engineering measure. As the product evolves, these target values will be used to evaluate the product's ability to satisfy customer requirements. There are really two actions needed here. The first is to ascertain how the competition, examined in step 4, meets the engineering requirements, and the second is to establish the value to be obtained with the new product.

In step 4 competition products were compared to customer requirements. In step 6 they need to be measured relative to engineering requirements. This ensures that both knowledge and equipment exist for evaluation. Also, the values obtained by measuring the competition give a basis for establishing the targets. This usually means obtaining actual samples of the competition's product and making measurements on them in the same way that measurements will be made on the product being designed.

Setting targets early in the design process is important; targets set near the end of the process are easy to meet but have no meaning. Some customer requirements will have ready-made target the requirement is measurable and provides a specific target. But for other requirements, realistic targets need to be set. These values define an ideal product and must be based on what is physically realizable, which is why it is essential to examine the competing products.

The best targets are set for a specific value. Less precise, but still usable, are those set within some range. A third type of target is a value made to be as large or as small as possible. Although measurable, these extremes are not good targets, since they give no information that tells when the performance of the new product is acceptable. However, evaluation of the competition should give at least some range for the target value.

2. Planning the remainder of the design project

Making a plan for the zproject is now a common practice for project management, since it is also part of design process, we go briefly through the steps of this activity. The design process diagram (Figure 3.1) showing the progression from establishment of need through product design is a guide to the intellectual tasks that must be accomplished during the design process. It is not, however, a plan that can be used for scheduling and for allocating personnel and other resources. Within this phase of the design process there is a block labeled *plan for project* and later, in the conceptual design phase, there is a block labeled *update plans.* Within these blocks we focus on efforts to develop and update the project plan and produce the documents that communicate the *goals, timing,* and *personnel* needed to develop the product (Figure 3.9).

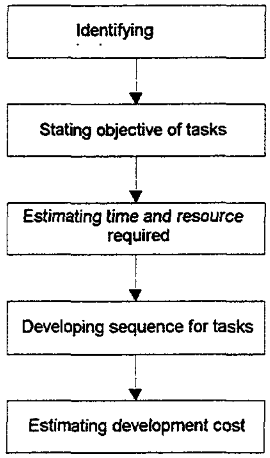


Figure 3.9 Steps for design project planning

A project plan is a document that defines the tasks that need to be completed during the design process. For each task the plan states the objective(s), personnel requirements, time requirements, schedule relative to the other tasks, and sometimes a cost estimate. In essence, a project plan is a document used to keep that project under control. It allows the design team and management to know how the project is actually progressing relative to progress anticipated when the plan was first established or last updated.

The best way to develop a schedule for a fairly simple project is to use a bar chart. This type of chart is often called a *Gantt chart* in project management term.

Two methods that can help in developing an efficient sequence of tasks in a project and estimating how long they will take are the *CPM* and *PERT* methods. *CPM* (critical path method) helps determine the most efficient sequence of tasks. *PERT* (program evaluation and review technique) aids in finding the best estimate of the total time the project will take. For theories concerning planning can refer to literature about project management.

3. Decomposing the design problem into subproblems

Most design problems are too large to solve as a single system. A product can be grouped by function into subsystems or grouped by form into assemblies. Each subsystem or assembly is a design problem in itself. In the ideal situation, during this first design phase the overall design problem can be *decomposed* as shown in Figure 3.10. Each block beneath the overall system block represents a separate subsystem that is functionally independent of the other subsystems. If the design problem concerns a mature device, the problem can sometimes be identified as the development of many specific assemblies.

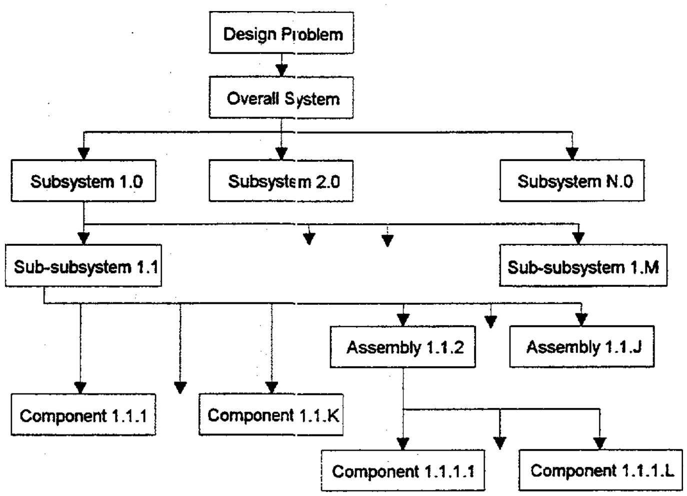


Figure 3.10 Problem decomposition procedure

An assumption is made during decomposition that each subsystem can be solved independently, which is often not true in mechanical design; since most functions require several components and each component may be important to several functions. The tree in Figure 3.10 does not possible show the inter-relation between sub-systems, thus it is very simplistic. Additional caution must be taken to avoid the incompatibility between sub-systems. A list should be made to show which of the sub-systems have relation between each other; normally relevant representatives from different sub-supplier or designers from different design teams have regular meeting for interface coordination.

4. Design records generating and the design review

As a result of using the techniques presented in this chapter, the following documentation contains following items will have been generated for problem understanding and planning of remainder:

- Description of customers
- Customer requirements
- Weighting of customer requirements
- Competition benchmark vs. customer requirements
- Engineering specifications
- Competition benchmark vs. engineering specifications
- Engineering targets and or project planning:
- Task titles
- Objectives of each task
- Personnel requirements for each task

- Time requirements for each task
- Schedule of tasks

This documentation plus the design notebook will give a complete description of the state of the design. With this information, a formal design review presentation can be made and management is given sufficient information to decide whether to continue with the project or to terminate it before more funds are spended.

3.1.3.2 The conceptual design phase:

A concept is an idea that can be represented in a rough sketch or with notes, in other words an abstraction, of what might someday be a product.

The flow diagram of conceptual design is shown in Figure 3.3. Here as with all problem solving, the generation of concepts is iterative with their evaluation. Also part of the iterative loop, as shown in the figure, is the generation of documentation, updating of the plans, and the decomposition of the problem into subproblems.

We will focus on two techniques: Functional decomposition and Generating concepts from functions. Many of the customer requirements are concerned with the functional performance desired in the product. These requirements become the basis for the concept generation techniques. The first technique aids in transforming the functions to concepts.

1. Functional decomposition by logic flow

In mechanical design, one can define function as the behavior of a human or of a machine that is necessary to accomplish the design requirements. It is actually the same for control system design. The different is that in the control system design, one needs to consider both hardware and software functional decomposition. The human is included in the definition because very few designs totally exclude human interface as part of their function.

Function can be described in terms of the logical flow of energy, material, or information. For example, in order to attach any component (material) to another, the human must grasp the component, position it, and secure it in place. These functions must be completed in a logical order: grasp, position, and then secure. In undertaking these actions, the human provides information and energy in controlling the movement of the component and in applying force to it. The three flows-energy, material and information-are rarely distinguishable. For instance, the control and the energy supplied by the human cannot be separated; however, it's important to note that both are occurring and that both are supplied by the human.

The functions associated with the flow of energy can be classified both by the type of energy and its action in the system. The types of energy normally identified with mechanical are mechanical, electrical, fluid, and thermal. As these types of energies flow through the system, they are transformed, stored, transferred (conducted), supplied, and dissipated. These are the "actions" of the system or the energy. Thus all terms used to describe the flow of energy are action words; this is characteristic of all description of function.

Function associated with the flow of material can be divided into three main types:

(1) Through flow, or material-conserving process: Material is manipulated to change its position or shape; some terms normally associated with through flow are position, lift, hold, support, move translate, rotate, and guide.
(2) Diverging flow, or dividing the material into two or more bodies; terms that describe diverging flow are disassemble and separate.
(3) Converging flow, or assembling or joining materials.

The goal of the functional modeling technique is to decompose the problem in terms of the flow of energy, material, and information. The forces detailed understanding of the functions of the product-to-be at the beginning of the design project. Although we use it here in the development of concepts, the functional decomposition technique is also very useful in understanding already existing designs and can be used in benchmarking and redesign as well as original design problems.

There are two basic steps in applying the technique and several guidelines for successful decomposition:

STEP 1: Find the overall function that needs to be accomplished.

This is a good first step to understanding the function. The goal here is to generate a single statement of the overall function, based on the customer requirements. All design problems have one or two "most important" functions. These must be stated in a single, concise sentence.

STEP 2: Decompose the function into subfunctions.

The goal of this step of concept generating is to refine the overall function statement as much as possible. There are three reasons for doing this:

a The resulting decomposition controls the search for solutions to the design problem. Since concepts follow function and products follow concepts, we must fully understand the function before wasting time generating products that solve the wrong problem.
b The division into finer functional detail leads to better understanding of the design problem.
c Breaking down the functions of the design may lead to the realization that there are some already existing components that can provide some of the functionality required.

The technique provides some guidelines for accomplishing the decomposition:

Guideline 1: Document what not how.

It is imperative that only what need to happen be considered. Detailed, structure-oriented how considerations must be suppressed. Even though we remember functions by their physical embodiments, it is important that we try to override this natural tendency. If, in a specific problem solution, it is not possible to proceed without some basic assumptions about the form or structure of the device, then document the assumptions.

Guideline 2: Use standard notation when possible.

For some types of systems there are well-established methods for building functional block diagrams. Common notation schemes exist for electrical circuits and piping systems, and block diagrams are used to represent transfer function in systems dynamics and control. Use these notations if possible.

Guideline 3: Consider logical flows.

It is necessary to consider the logical relationships between the functions to determine their sequence. Instance of "and's" and "or's" are often important in the functional flow. Standard logic symbols or words can be utilized to note these branches.

Guideline 4: Match inputs and outputs in the functional decomposition.

Input(s) to each function must match the output(s) of the previous function. The inputs and outputs represent energy, material, or information. Thus the flow between functions can be viewed as conveying the energy, material, or information without change or transformation.

Guideline 5: Break the function down as finely as possible.

This is best done by starting with the overall function for the design and breaking it into the separate functions in block-diagram style. Some conventions that are helpful in developing a block diagram are:

- Let each block in the diagram represent a function that must be performed: a change or transformation in the flow of material, energy, or information. One goal is to continue to decompose the function until each block represents the function at its most basic level.
- Number each first-level breakdown as 1.0, 2.0 .... Then the subfunctions fur function 1.0 can be labeled as 1.1, 1.2,... and the subfunctions for 1.2 can be labeled 1.2.1, 1.2.2....and so on.
- Let each line connecting blocks represent the flow of material, energy, or information.
- Let energy, material, or information that is flowing be represented by a noun or a noun clause and the function by a verb acting on the noun.

It must be realized that the function decomposition cannot be generated in one pass and it is an iteration process to develop the suggested diagrams. However, it is a fact that the design can only be as good as the understanding of the functions required by the problem. This exercise is both the first step in developing ideas for solutions and another step in understanding the problem. The functional decomposition diagrams are intended to be updated and refined as the design progresses.

2. Generating concepts from functions

The second technique in concept generation uses the functions identified above to promote ideas. There are two steps to this technique.

STEP 1: Developing concepts for each function.

The goal of this first step is to generate as many concepts as possible for each of the *functions identified in the decomposition.*

During developing of a list, if there is a function for which there is only one conceptual idea, then this function needs to be reexamined. There are few functions that can be fulfilled by one, and only one, concept. The following situations could explain the lack of more concepts:

1. The designer has made a fundamental assumption without realizing it. It is right to make such an assumption, providing there is an awareness that an assumption has been made.
2. The function is directed not at what but at how. If one idea is built into a function, then the true function of the design must be reconsidered.
3. Domain knowledge is limited. In this case, help is needed to develop other ideas.

STEP 2: Combing concepts.

The result of applying step 1 is a list of concepts generated for each of the functions. Now we need to combine the individual concepts into complete conceptual designs. The method here is to select one concept for each function and combine those selected into a single design. But there are pitfalls to this method: First, if followed literally, this method generates too many ideas.

Second, problem with this method is that it erroneously assumes that each function of the design is independent and that each concept satisfies only one function. Generally, this is not the case. As overall ideas are generated, often the same concept can satisfy more than one function.

Third, the results may not make any sense. Although the method is a technique for generating ideas, it also encourages a coarse ongoing evaluation of the ideas. Still, care must be taken not to eliminate concepts too readily; a good idea could conceivably be prematurely lost in a cursory evaluation. A goal here is to do only a coarse evaluation and generate all the ideas that are reasonably possible. In the next chapter we will evaluate the concepts and decide between them.

3.2 Conceptual design of underwater control system

Design criteria are stated as things that should or should not be incorporated into the design, or as minimum or maximum limits that should be placed on the design. Minimum design criteria should be established for the areas of reliability, maintainability, testability, producibility, supportability, and cost. These criteria must address specific points in each area. The design criteria should be such that, if met, the final system design will meet all specified product requirements. The emphasis on design criteria is to stress that it is extremely important to establish the detailed design criteria for a system early in the design process in order to ensure that the final system design meets the product specification requirements.

In the previous sections, we introduced methods used in a product design process, such as QFD (Quality Function Deployment) method, method for problem decomposition and method for generating concept from functions. In this section, we will try to apply these methods and techniques to solve the design problem we have, the underwater control system.

3.2.1 Understanding the design problem

1. Identifying the customer(s)

The step one in QFD method is to identifying the customer, for our case, unlike the consumer product, the customer group is small. For the nature of the product, the customer will be found among the following branches (Table 3.2).

Table 3.2 Customer base for underwater equipment

Customer	Application area
Oil Company	Seabed contour, composition, obstruction survey Routine inspection of structures Damage repair/inspection
Installation company	General underwater civil engineering work Route profiling Site preparation Pipeline/cable trenching Inspection during laying of pipelines/cables Connection of pipelines and risers Reburial after repairs Repair of fixed structures, seabed completion, pipelines, X-mas Trees etc. Replacement of valves Rescue of Equipment
Research organization	Geological survey Geophysical survey Sample collection
Salvage organization	Training of divers Rescue of divers Underwater transport of divers

From Table 3.2, we will find out that the installation company has the most intensive use of underwater equipment, so most of the operators of underwater equipment are installation companies. However, installation company is a service supplier, most of their services are purchased by oil company, even they are not directly involved in operating those equipment, they are also the end users of the services. Therefore, all the equipment designed to be used in an oil field, the oil company will have the last word. That means, when we design a product, we should not just listen to the operator, but also the service end user- the oil company.

2. Determining customer requirement

After we have identified our customer, the next step is to determining customer requirement. Since underwater equipment is a range of totally different equipment, therefore it is not possible to find out customer's requirement for all the equipment they need. However, there are some common characteristics for underwater equipment; many of the requirements regarding control system will be decided by those characteristics. We will discuss these characteristics later in the chapter.

Since different type of equipment demands different type of control system, and different control system has different characteristics, so without a defined product, the other steps in QFD methods will not be possible to complete. We will discuss the customer requirement and other part of QFD method later in Chapter 5, where we use a Tie-in system as example to complete the whole procedure. In this section, we will try to outline some of the most common characteristics of underwater equipment control. These characteristics will be served as design criteria for all the underwater control system.

3.2.2 General Concept of model for underwater equipment

What we call an underwater equipment control is normally refer to a system which is located at a distance with the operator and submerged in water. The systems are operated directly or possible to be intervened by human operator. The systems are normally mobilized and working in complex surroundings.

It is difficult to make a complete model to contain different kind of underwater equipment, but from control system point of view, it is possible to make a general in sense of the relation between operator, control system and the actuation system. Such a model can be presented in Figure 3.11. In this model, we use ROV as the controlled system to illustrate this model

From this relative simple conceptal model, we can find the most characteristics of an underwater equipment from control point of view. A common character for the underwater equipment is that all the systems are located in a distance to the operator, which means the directly manual operation by the operator is normally not feasible. In order to accomplish such a control, an interface between human operator and the assistant device (normally computer or similar) will be carried out. The most important factor is that all the activities are occurring at a distance to the operator, the environment condition made it is impossible to the operator to operate the system at the action spot. Because this special situation, the characteristics of controlling an underwater equipment are different to land based system. In following sections, we are going to discuss related topics related to distance and human centered control.

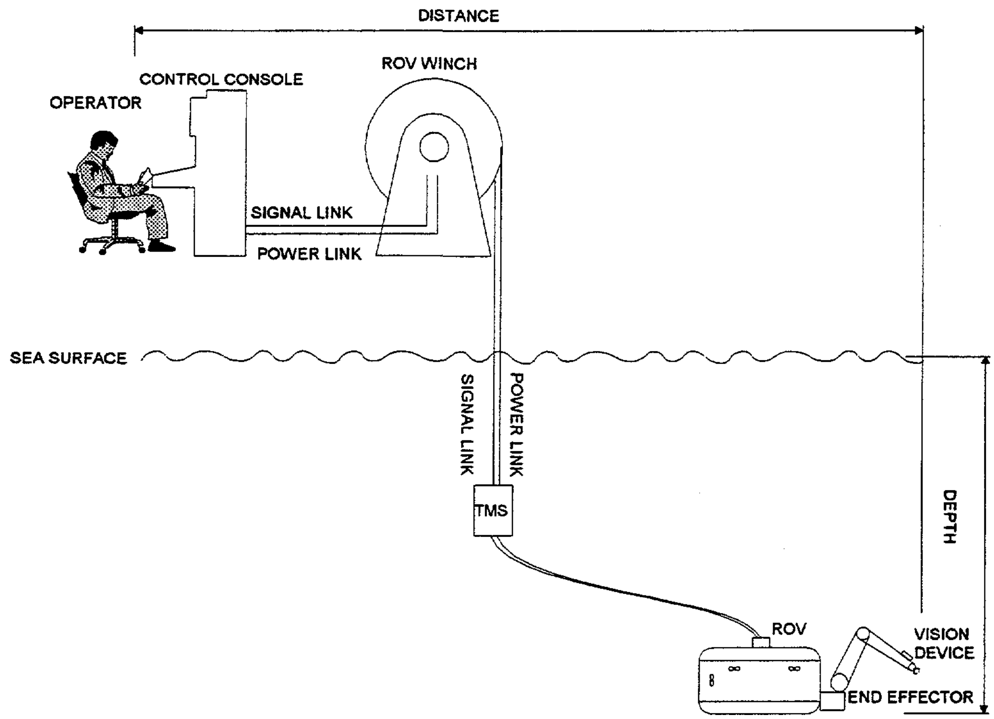


Figure 3.11 General concept model for underwater equipment configuration

3.2.2.1 Design Objectives

There are three primary objectives within human centered design.

The first objective of human centered design is that is should *enhance human abilities. This* dictates that humans' abilities in the roles of interest be identified, understood, and cultivated. For example, people tend to have excellent pattern recognition abilities. Design should take advantage of these abilities, for instance, by using displays of information that enable users to respond on a pattern recognition basis rather than requiring more analytical evaluation of the information.

The second objective is that human centered design should help *overcome human limitations.* This requires that limitations be identified and appropriate compensatory mechanisms be devised.

The third objective of human-centered design is that is should *foster user acceptance.* This dictates that users' preferences and concerns be explicitly considered in the design process.

The designer can use the following principles to make the checklist and evaluate the design.

- Visibility, by looking, the user can tell the state of the device and the alternatives for action.
- A good conceptual model, the designer provides a good conceptual model for the user, with consistency in the presentation for operations and results and a coherent, consistent system image.
- Good mappings, it is possible to determine the relationships between actions and results, between the controls and their effects, and between the system state and what is visible.
- Feedback, the user receives full and continuous feedback about the results of actions.

3.2.2.2 Human centred control system

The roles of humans in a system can be addressed in several ways. There are obvious roles such as operator, maintainer, and manager, which denote jobs associated with developing and operating complex systems. Within these roles, people are called upon to exhibit various levels of skill, judgment, and creativity to achieve a range of objectives.

It is imaginable, and in some cases inevitable, that automation of skill, judgment, and perhaps even some aspects of creativity will increasingly be feasible. However, regardless of levels of automation, people will remain responsible for operations of complex systems. People may be geographically remote from these operations; and they may be supported by sophisticated computer-based decision aids; nevertheless, they will have ultimate responsibility.

Since people will inevitably be responsible for system operations, it is essential that people perceive the nature of these responsibilities and have appropriate levels of authority to fulfill them. Consequently, design philosophies and design methods associated with developing complex systems should explicitly reflect the primacy of supporting people to successfully be "in charge." This conclusion leads to the straightforward assertion that design objectives should be to support humans to achieve the operational objectives for which they are responsible.

From this perspective, the purpose of design is not to control technology to achieve operational objectives. Instead, design should be oriented toward integrating technology and other resources to support people in ways that are appropriate and conducive to their fulfilling the responsibilities associated with their roles. This is the essence of human centered design.

1. The role and function of Supervisor

There are four types of interaction for human to interact with control system - as occupant of workspace; as power source; as sensor; and as controller -- form the basis for the study of the human factors that play a major role in the design of a control system.

Two reasons for this concern with human factors are quality and safety. Products are perceived to "work as they should" if they are comfortable to use (these is a good match between the device and the person in the workspace); they are easy to use (minimal power is required); their operating condition is easily sensed; and their control logic is natural; or user-friendly. Of equal importance is the concern for safety. Customers assume that neither they nor others will be injured, nor that property will be destroyed when a product is in use.

We will also make use of a traditional classification of behavioral activity according to apparent physiological area to define the supervisor's role as sensor and controller. The supervisor offers following functions, such as:

- (S) sensory (vision, hearing, taste, touch, smell, vestibular senses),
- (C) cognitive activity without apparent sensory or motor components (remembering, making decisions), and
- (R) response or motor functions (referring usually to skeletal muscle activity). Clearly the body's major sensors have muscles to control them, and muscles have internal or interceptive sensors to close their control loops.

2. Sense and sensitivity

The human sensory system has far more neurons than the human-motor system, and there are various ways to classify its functions.

The five classic categories: vision; hearing; touch; taste; and smell do not specifically include various pain sensations both on the skin and internal to the body, or heat and cold (unless these are categorized under touch). They do not include the important sensors of translational acceleration (the otolith organs of the inner ear or auditory vestibule) and the sensors of rotational acceleration (the semicircular canals). Nor do they include the various muscles and tendon organs, the proprioceptive (literally "self-sensing") or kinesthetic (motion-sensing) organs. One researcher claimed the body has over 200 distinct senses (Sheridan and Ferrell, 74).

The senses can be separated only to a limited degree. In ordinary manipulation the skin senses and the proprioceptors work together to sense spatial properties. In maintaining the postural balance, vision, the vestibular senses, and the proprioceptors work as a unit to sense dynamic equilibrium. In most everyday activities, information from all of the senses is integrated and provides redundancy. This is illustrated by the degree to which a person can compensate for a lost sense in tasks where redundant information is available, e.g., a blind person walking down a hallway using sound echoes to maintain his orientation.

We can use mechanical device extended human's capacity from land down to deep sea and out in the space. We can also use instrument to overcome human's limitation in gathering information from the sea.

As we know, all the underwater equipments are distance from the operator, and the operator can not see, feel, hear or touch the surrounding to the system, neither operate the system. That means due to the environmental condition, the human has lost all the senses required for a successful operation. The purpose here is to give the human operator the lost senses back as much as possible.

A good illustration of a human limitation is the proclivity to make errors. Humans are fairly flexible information processors, an important ability, but this flexibility can lead to "innovations" that are erroneous in the sense that undesirable consequences are likely to occur.

3. The levels of human behavior, "Skills, Rules, Knowledge"

Rasmussen introduced a paradigm for describing in human behavior three levels:

- *skill-based behavior* (continuous, typically well-learned, sensorimotor behavior analogous to what can be expected from a servomechanism),
- *rule-based behavior* (what an "artificially intelligent" computer can do in recognizing a pattern of stimuli, then triggering an "if-then" algorithm to execute an appropriate response), and finally
- *knowledge- based behavior* ("high-level" situation assessment and evaluation, consideration of alternative actions in light of various goals, decision and scheduling of implementation a form of behavior machines are not now good at). Figure 3.12 is an abbreviated version of Rasmussen's qualitative model showing in particular the nesting of skill-based, rule-based, and knowledge-based behavioral loops.

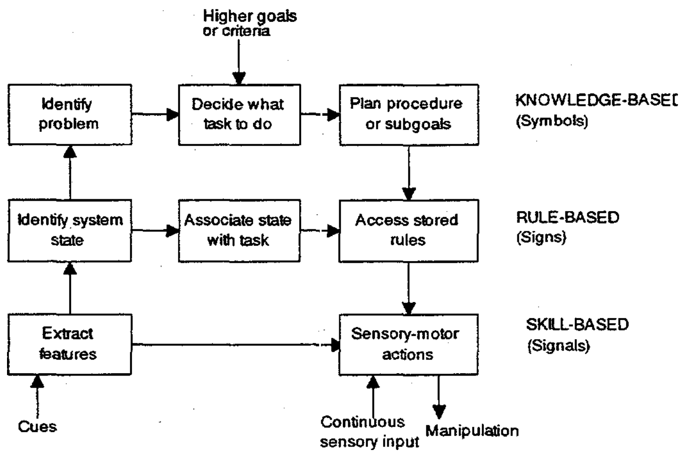


Figure 3.12 Model for levels of human behavior

4. The human as source of power and controller

Humans often have to supply some force to power a product or actuate its controls. Human force-generation data is often included with anthropometric data. This information comes from the study of biomechanics(the mechanics of the human body). The average human strength for differing body positions are well documented in many literatures, for example some military standards and human ergonomic handbook. Although only averages, these values do give some indication of the maximum forces that should be used as design requirements.

Most interfaces between humans and machines require that humans sense the sate of the device and, based on the data received, control it. Thus product must be designed with important features readily apparent, and they must provide for easy control of these features.

There are many ways to communicate the status of a product to a human. Usually the communication is visual; however, it can also be through tactile or audible signals. The basic types of visual displays are in Figure 3.16. When choosing which of these displays to use, it is important to consider the type of information that needs to be communicated. Table 3.4 relates five different types of information to the types of displays.

In general, when designing controls for interface with humans, it is always best to imply the structure of the tasks required to operate the product. From the characteristics of the short-term memory, we learned there that humans can deal with only seven unrelated items at a time. Thus, it is important not to expect the user of any product to remember more than four or five steps. One way to overcome the need for numerous steps is to give the user mental aids.

3.2.3 Operated from distance

Since there is a gap between the input device and the actuation system, and the human operator is constantly involved in the control process, so the response time and the modeling of human operator become most important factors for such systems. The response time is one of the major factor to evaluate the performance of a control system.

3.2.3.1 Dependent on instrument feedback

The operator and the underwater equipment are separated from each other by a large quantity of water. There is no directly visual, audio or tactile information available to the operator. That means all the channels for human information gathering are blocked, and for any kind of system, it is not possible to be operated without feedback information, the operator has to be updated what is going on there. In order to get back those lost senses, the only way is getting that information through different kind of instrument and sensors.

Feedback sending back to the operator information about what action has actually been done, what result has been accomplished, is a well known concept in the science of control and information theory.

1. Feedback signal for mechanical device

For underwater operation, different types of feedback are need for the equipment closed loop control; we can use this requirement as one design criterion for feedback signal.

For most of the equipment, the most important reference signal is the position reference. Both absolute and relative position references are needed for almost all the actuation device unless mechanical limit is sufficient for that device. With more advanced control, for example manipulator, etc., in order to get more precise and fast control of each of the joints, the velocity and acceleration reference are also required.

The force and torque signals are for more advanced manipulation control, for this type of operation, among other things, the force and torque can be used for force and torque control of the manipulator. This kind of reference signal will be essential for precise grinding, component or valve installation, etc..

Attitude references are those signals to tell the status of the vehicle under the sea, that includes heading, water depth, height above bottom and roll and pitch angles. Those signals are the basic reference for the automatic vehicle control (autopilot).

The pressure and temperature references are used to monitor the internal status of the whole system. For hydraulic system, the work loop and return loop pressure are very important criteria about how the system is working, if there is a leakage or block. The use of temperature reference is about the same, it can be used to check if there is an overload or similar.

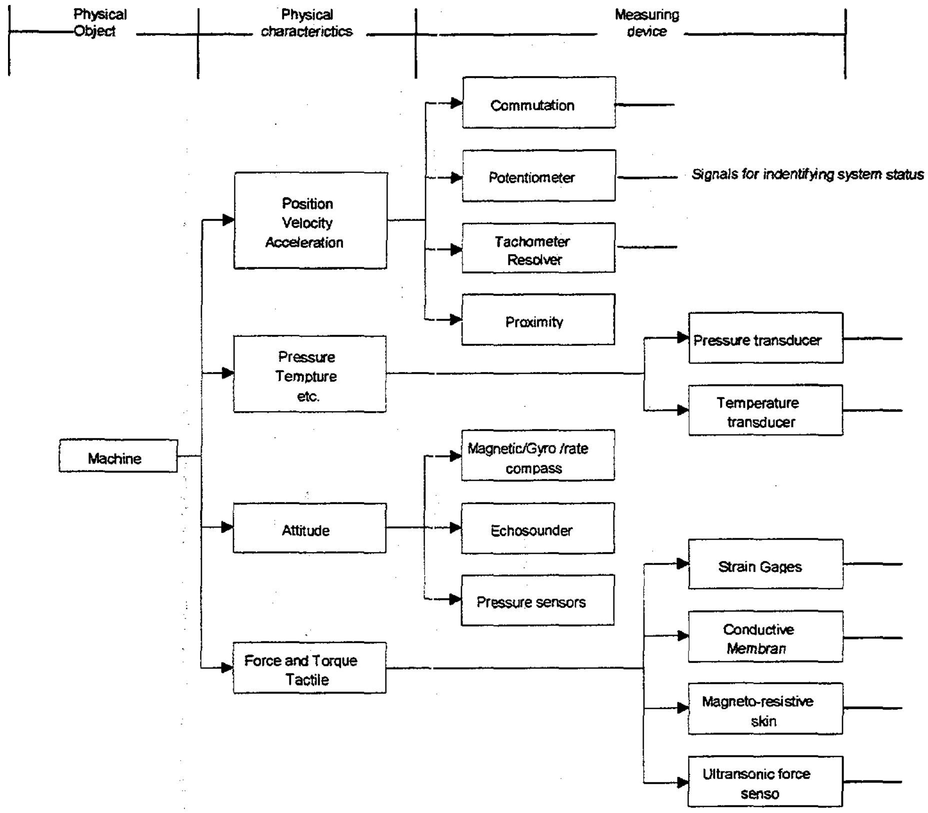


Figure 3.13 Feedback signal and sensor types for close-loop control

2. Feedback signal for operator decision making

Figure 3.13 and Figure 3.14 show the signal and sensors used for close-loop control for operator information gathering.

3. Human Computer Interaction and display

This is a very important property in teleoperation especially in underwater operation, which is difficult to define, but of the greatest interest since it allows the operator to develop a control strategy. The importance of visual feedback is well known, but force feedback (which cannot be envisaged with on-off control or computer peripherals) is also very important.

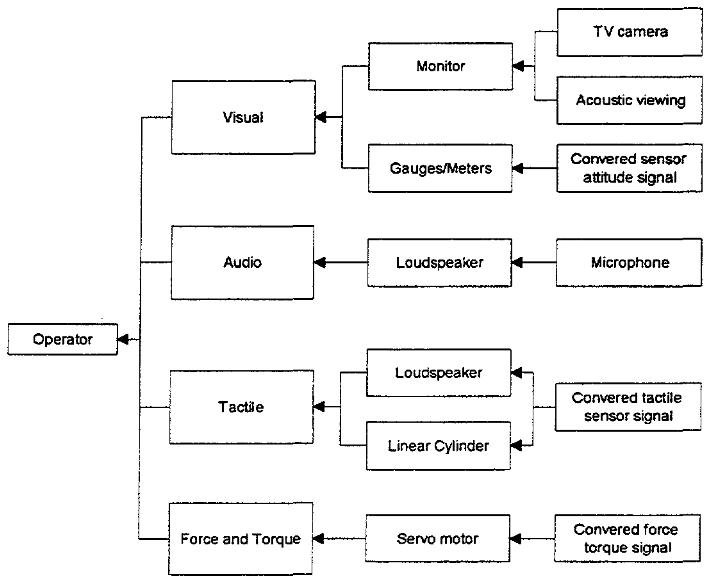


Figure 3.14 Feedback signals for operator

For the cognitive approach to human-computer interaction, there are many theories in cognitive science and cognitive psychology can be applied to the human-computer interface to make the processing of information by the human easier and more efficient. Similar to other human-based tasks, the computer user perceives, stores, and retrieves information from short- and long-term memory, manipulates that information to make decisions and solve problems, and then carries out responses.

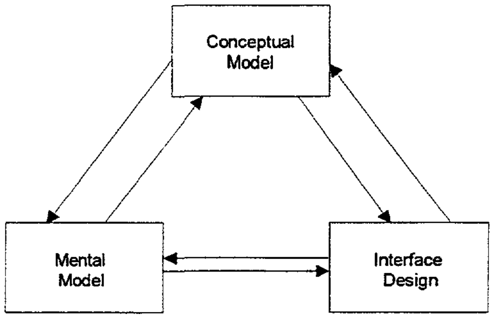


Figure 3.15 Cognitive approach to User Interface design

Interacting with a computer through the interface design is a cognitive activity on the part of the user. The user must remember many things and then be able to implement and execute the appropriate commands. The user must retain cognitive information about the particular system or program. The user must also know about how to interact with computer systems in general by having some kind of cognitive model of how computers behave and knowing how to cognitively decompose a task into workable units. This division between specific and general knowledge has been termed as a division between syntactic and semantic information.

To address the cognitive behavior in more detail, consider, as an example, that you wish to reorder some of the paragraphs in a memo, originally prepared using a word processor, to make the memo more readable. Smith *et al.* (92) concluded that the user would sequence through the following seven stages:

- Establishing the goal
- Forming the intention
- Specifying the action sequence
- Executing the action sequence
- Perceiving the system state
- Interpreting the state
- Evaluating the system state with respect to the goats and intentions

These stages do not have to be performed sequentially. As examples, multiple intentions may be formed before an action sequence is determined. If the evaluation determines that the goal has not been satisfied then new intentions are constructed.

The interface designer must understand the cognitive activities of the user in order to design an effective and easy-to-use interface. The interface design process utilizing the cognitive approach can be stated pictorially in. Three concepts are important. First, the conceptual model is a description of the computer system or the interactive program in engineering or programming terms that it is accurate, consistent, and complete. The second concept, the mental model, is the model that the user forms of how the computer system or program works; this mental model guides how the user structures the interaction task. The mental model is built up through interactions with the third concept, the display representation, which provides the user, along with off-line documentation, the off-line view of the conceptual model. The interface designer's goal is to choose the displayed information so that the mental model can, like the conceptual model, be accurate, consistent, and complete. A test of the success of an interface is a comparison of the user's mental model to the conceptual model (Figure 3.15).

Graphics and spatial representations exhibit many similarities to the metaphors and analogies. In almost all cases for the metaphors and analogies, they provide a spatial representation to the information that can be easily mapped to graphical displays.

Some experiments indicate that having the ability to make use of the manipulation of spatial information may make human-computer interaction tasks easier to perform.

Many times, an assumption is made that graphics will always make the task-easier. As can be seen from a quick review, this is not always the case. Merely presenting information in a graphics display will not enhance user performance. The graphics have to be chosen carefully. Graphics could be used to make the invisible visible, for representing physical systems and nonspatial or abstract knowledge.

Another application of using graphics to represent physical systems are the work of Rasmussen on interface designs for process control tasks. The process control systems, such as the energy plants studied by Rasmussen, are so complex that all the system cannot be represented on one screen. A solution to this problem is to design the interlace in levels so that a user can get more detail by successively zooming to these different levels. The design problem is to determine the levels that should be used. These levels should be on operator interviews and designer's experience in that industry. The levels chosen may range from very low level information, such as valve settings or steam and water flow; to high-level information, such as company profits and plant safety. While they are concentrating mostly on the high-level information the operator can access the low-level information as needed for the decision and problem solving. The research shows that surprisingly little empirical research has been performed on the effectiveness of these kinds of displays.

To use graphics for nonspatial information, the designer must determine how to organize the information on the display. Simply using an organized table, which provides some amount of spatial information, can increase user performance close to levels of physical representations using graphics. Organization to nonspatial information can also occur through the use of display devices such as hierarchical structures and networks.

Advantages and disadvantages of the use of graphics in interface designs can be found in Table 3.3. A summary of advantage and disadvantage for using graphics is listed as follow:

Table 3.3 Advantages and Disadvantages of Graphics (Smith, *et. al*, 92)

Advantages	Disadvantages
- Useful for instantiating metaphors - Useful for providing mapping to physical systems - Useful for making the invisible visible - Provides organization to abstract information - People represent even abstract entities spatially	- For physical systems usually too much information to fit on a screen - User must learn the limits of each metaphor - If abstract information, may be difficult to re quire information about organization from experts

Guidelines for Using Graphics (Smith, *et. al*, 92):

- If using a metaphor in the design, graphics in the form of icons can be used to instantiate the metaphor
- If representing a physical system through graphics, use levels in the design so that more information can-be represented
- If representing abstract tasks, acquire knowledge from experts to use a guide for organizing the information on the screen.
- Use graphics to organize information

3.2.3.2 Response Time.

Generally, "immediate" actuation of subsea devices is not required for most of subsea system; for many of the functions, a delay of up to 30 seconds is acceptable, of course the shorter response time gives better performance. However, for some of the equipment, "immediate" response is still a requirement. The nature of these operations requests as short response time as possible, especially the underwater vehicles and underwater manipulators. For such systems, a response time should be limited within seconds; too long response time will cause instability of the operation.

Because all the actuation occurs at distance, so the control system design should consider both the time for control signals to reach the subsea system (signal time); the time for subsea signal processing (processing time); the time for the controlled device (e.g. valve) and time to shift actuator's position (actuation time). The total response time T_R is the sum of all those times.

That is $T_R = T_S + T_P + T_C + T_A$ (s).

T_R - Total response time.
T_S - The time for signal transfer.
T_P - The time for signal processing.
T_C - The time for the control device.
T_A - The actuation time.

For the correcting action, that is if something unexpected is happening under the sea, then the total response correspondingly will include the time for acquiring sensor signal and processing (acquiring time), the signal time and time for the operator to take action. Then the formula will become:

$$T_{RS} = T_R + T_{Ac} + T_S + T_O \text{ (s)}$$

T_{RS} - Total response while human operator is supervising the operation.
T_{Ac} - The time need for acquiring necessary information.
T_O - The time used by operator for cognition, decision making and action.

The time need for the human operator is very difficult to define, since it involves too many factors, e.g. the experience, environment, etc.. In order to integrate the human operator better in supervisory operation, many researchers have tried to develop mathematics model to present human operator in a computer assisted supervisory environment. Eberts, *et. al* and Woodson, *et. al* (92) have documented many experiment results of human response to different input. The time delays can be modeled into an equation to represent the dynamic of the system. These theories and models for human centered supervisor control will be introduced in section 3.3.

In selecting the type of controller, it is important to make the actions required by the system match the intentions of the human. It is important to make sure people can easily determine the relationship between the intention and the action and between the action and the effect on the system. A product must be designed so that when a person interacts with it, there is only one obviously correct thing to do. If the action required is ambiguous, then the person might or might not do the right thing. Table 3.5 is the principle of using feedback signals to help the operator's decision making.

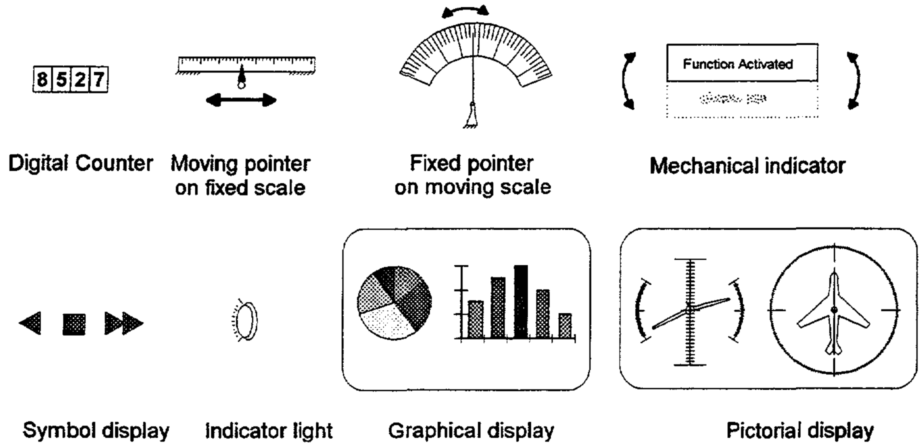


Figure 3.16 Types of visual displays

Table 3.4 Appropriate uses of common visual displays

	Exact value	Rate of change	Trend direction of change	Discrete information	Adjusted to desired value
Digital counter	☺	☹	☹	☺	😐
Moving pointer on fixed scale	☺	☺	☺	☺	😐
Fixed pointer on moving scale	☺	☺	☹	☹	☹
Mechanical indicator	☹	☹	☹	☺	☹
Symbol display	☹	☹	☹	☺	☹
Indicator light	☹	☹	☹	☺	☹
Graphical display	😐	😐	☺	☺	☺
Pictorial display	😐	☺	☺	☺	☺

☺ - Recommended 😐 - Acceptable ☹ - Not suitable

3.2.4 Environment requirement

For all the underwater equipment today, the environment requirement becomes more and more important of operating the equipment. The equipment itself has requirement on effects of water depth, currents and turbidity, marine life, seaflour condition and operating temperatures. The environment has also requirement of leakage dumping, noise generating, etc.. Different area has different requirement on these factors. The designer of the system has to check against their local regulation and requirement while they are doing the design.

Table 3.5 Recommendation of using feedback signal (Woodson, *et. al*, 92)

A.	Use visual signs when:	
	-	the message is complex, long or will be referred to later the message deals with location in space;
	-	the message does not call for immediate action;
	-	the receiving location is too noisy for auditory signals;
	-	the person receiving can remain in one place;
	-	the person receiving is overburdened by the auditory system
B.	Use the auditory signals when:	
	-	the message is simple, short, or will not be referred to later the message deals with events in time;
	-	the message calls for immediate action;
	-	the person receiving has to move around for the job;
	-	the person receiving is overburdened by the visual system;
	-	the receiving location is too bright or too dark when adaptation integrity is necessary;
	-	the displayed information occurs randomly and must immediately capture the attention of the operator
C.	When using visual signs:	
	-	consider printing style, size, and location use stereotype or standard symbols select appropriate colors.
	1.	red is used to alert that the system is inoperative
	2.	flashing red is used to denote an emergency condition that requires immediate action
	3.	yellow is used to indicate a marginal situation in which caution is necessary or unexpected delay may be encountered
	4.	green is used to indicate all conditions are satisfactory
	5.	white is used to indicate transient or alternative conditions
	6.	blue is used to indicate an advisory situation ensure luminance and sharp contrast with the background ensure that they are shaded or out of direct sunlight ensure that they are not subject to color detection confusion
D.	Auditory signals should:	
	-	have a signal level 15 dB above the masked threshold (defined as the level required for 5% correct detection) for 100% detectability and for a rapid response;
	-	have a signal level less than 30 dB above the masked threshold to minimize generated to the operator have a single pitch between 150 and 1000 Hz;
	-	have a pulse spacing compressed to increase urgency cease only after the operator responds appropriately;
	-	be consistent with others already in use in the plant;
	-	not be confused with the noise generated from the machining process

3.3 Supervisory control and Model presentation

Numbers of researchers have made effects to setup some sort of mathematics presentation of supervisory control. In those control theories, the links are closed with the human link, which will involve a number of delays and unpredictable factors. The following are some of the basic models.

3.3.1 *Concepts of Supervisory control*

1. The Basic Supervisory Control Paradigm

Figure 3.17 illustrates the basic concept of supervisory control, showing separate computers for loop local to human and loop remote from human, separated by a barrier of distance, time or inconvenience. The human operator provides largely symbolic commands to the computer. However, some of the commands may be analogical in order to point to objects or otherwise demonstrate to the computer relationships that are difficult for the operator to put into symbols. The local or human-interactive computer thus should be human-friendly, able to indicate that it understands the message, and able to point out that a specification is incomplete. In this way it should help the operator to edit the message correctly. It also needs to interpret signals from the distant telerobot, storing and processing them to generate meaningful integrated graphic displays. Finally, this local human-interactive computer should contain a knowledge base and a model of the controlled process and task environment and be able to answer queries put to it by the operator.

Meanwhile, the subordinate "remote" or task-interactive computer that accompanies the controlled process must receive commands, translate them into executable strings of code, and perform the execution, closing each control loop through the appropriate actuators and sensors.

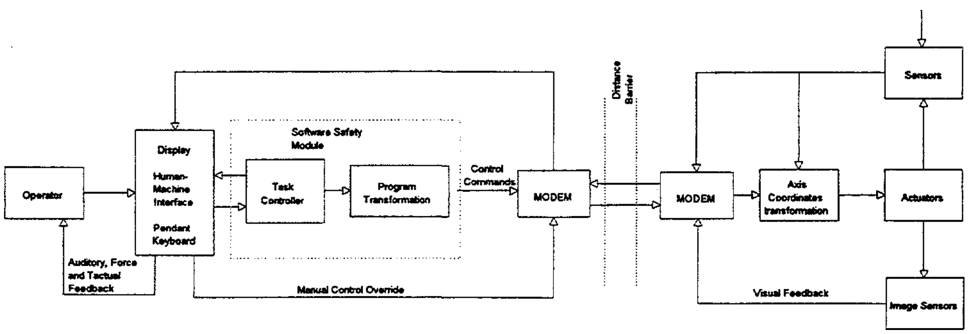


Figure 3.17 Basic concept of telerobot supervisory control

2. Five Generic Supervisory Functions

Sheridan (92) summarized that the human supervisor's functions are

1) planning what task to do and how to do it,
2) instructing (or programming) the computer what was planned,

3) monitoring the automatic action (which means to make sure all is going as planned and to detect failures),
4) intervening (which means that the supervisor supplements ongoing automatic control activities, takes over control entirely after the desired goal state has been reached satisfactorily, or interrupts the automatic control in emergencies to specify a new goal state and reprogram a new procedure), and
5) learning from experience (so as to improve planning in the future).

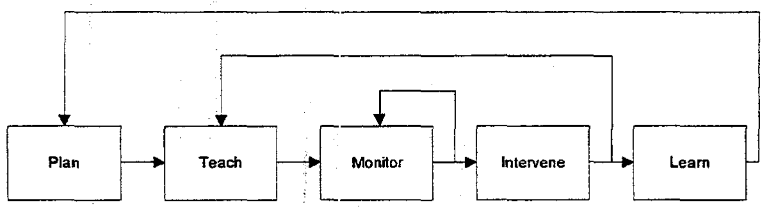


Figure 3.18 Five supervisor functions as nested loops

- Planning

Supervisor planning is a continuous process. It contains that:

(1) obtaining experience by understanding of the physical process to be controlled, including the constraints set by nature and circumstances surrounding the job,
(2) setting goals that are attainable, or objectives along with tradeoffs, that the computer can "understand" sufficiently well to give proper advice or make control decisions, and
(3) formulating a strategy for going from the initial state to the goal state.

This part of function is most difficult to model, because the planning can be split into two different parts; long term learning to obtaining experience and short time plan the task. So planning itself is an iterative process, along with more experience the supervisor obtained; the result of planning work is also better.

- Instructing the computer

The supervisor must translate goals and strategy into detailed instructions to the computer such that it can perform at least some part of the task automatically, until the instructions are updated or changed; or the human takes over by manual control. This includes knowing the requisite command language sufficiently well that goals and instructions can be communicated to the computer in correct and timely fashion.

- Monitoring automatic control

Once the goals and instructions are properly communicated to the computer for automatic execution of that part of the task, the supervisor must observe this performance to ensure that it is done properly, using direct viewing or whatever remote sensing instruments are available. The prompt detection of the presence and location of failures, or of conflicts between actions and goals, and the anticipation that either of these is about to occur, are essential parts of the supervisor's job.

- Intervening to update instructions or assume direct control

  If the computer signals that it has accomplished its assigned part-task, or if it has apparently run into trouble along the way, the human supervisor must step in to update instructions to the computer or to take over control in direct manual fashion, or some combination of the two. Since the controlled process is an ongoing dynamic system, not a machine that can be arbitrarily stopped and started again like a computer, the takeover itself must be smooth so as not to cause instability. Similarly, reverting to the automation must be smooth.

- Learning from experience

  The supervisor must ensure that appropriate data are recorded and computer-based models are updated so as to characterize current conditions with the most accurate information. Historical data must continuously be analyzed for trends or contingencies leading to abnormalities. Algorithm and model should be updated from the experience learnt from previous practice. All such information must be in a form usable in the future in the four proceeding steps.

3. Multiplicity of Loops and Levels in Supervisor Control

We may view the supervisor functions as operating within three nested control loops, as shown in Figure 3.18. The innermost loop, monitoring, closes on itself. That is, considering what evidence is interesting, the supervisor redirects ones' attention and formulates hypotheses or makes minor system adjustments in the automatic control system that require no significant intervention. The middle loop closes from intervening back to teaching, i.e., human intervention usually leads to programming of a new goal state to the process. The outer loop closes from learning back to planning; intelligent planning for the next subtask is usually not possible without learning from the last one. The three supervisory loops operate at different time scales relative to one another. Revisions in monitoring behavior take place at brief intervals. Interventions and/or reprogramming occurs at somewhat longer intervals. Learning and revision in task planning occur only at still longer intervals.

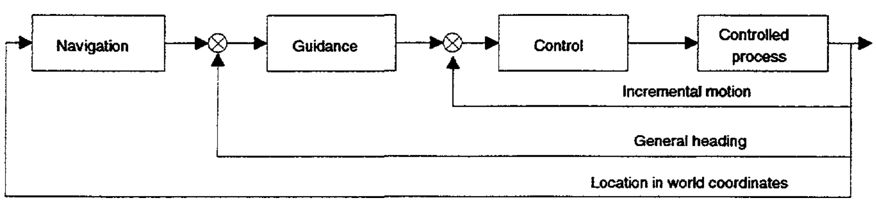


Figure 3.19 Navigation, guidance, and control as nested loops

Supervisory control is the way spacecraft and ROV are controlled, so that the five-step functional fits that situation rather well. Figure 3.19 shows navigation, guidance and control as nested loops as applied to an aircraft or another vehicle under multi-level control. In modern aircraft the supervisory control functions apply when the autopilot is used, but at the pilot's option all three loops can be and often are under manual control.

The innest loop -- Incremental motion -- is normally under control of computer or similar instrument. The sensory signals from various sensors are about position, orientation, etc. From controlled process are fed back to the control system (some times, it is also represented by local control computer). The difference between reference and output will be correct instantly. This loop could be fully automized.

The secondary loop - General heading - is normally under manual control. The information received from the sensor system is converted to a form can be utilized by the operator. The operator gives instruction directly or via a computerized equipment to local control unit to achieve the general heading. This loop could also be a combination of manual and automatic control. At some situation where the operation condition is well known or predictable, this loop can also be totally taken over by computerized control unit. This type of operation is normally referred as "Autopilot".

The outmost loop - Navigation - up to today can be only achieved by a human operator. The navigation information comes from different sources (map, satellite, etc.) can only be used as a reference to human operator. Computer generated map or coordinates of the vehicle will be used by human operator to locate his position or plan the journey. This part of work will be the responsibility of human operator; the best which a computer can do is to supply some alternative for human operator to choose from.

3.3.2 Theories of Supervisory control modeling

3.3.2.1 Manual control models

There are two reasons for modeling the human operator in manual control tasks: the one motivated by practical application, and the other by scientific interest in the general question of human performance.

1) The engineer is interested in total man-machine performance which he cannot predict from knowledge of the machine components alone. High-speed modern aircraft cannot be made which satisfy criteria for stability and handling unless the designer can write equations for the human-operator response which he can solve simultaneously with those for the dynamics of the aircraft. This is true because the quality of performance of either the human or the machine component by itself does not determine the quality of system performance.

2) The second reason for modeling the human operator in control systems is that the control task, by virtue of its being simple, well defined, and experimentally manageable, provides an excellent yardstick for investigation of primitive sensing, decision making, and response characteristics of the human organism. For these reasons, psychologists and physiologists have become increasingly attracted to the use of simple manual control tasks in the laboratory with no interest in practical problems of matching man to machine.

The engineer must be concerned with practical, usable models of human performance, as well as with research models. The ultimate aim is to relieve the human of those perfunctory tasks which can better be automated; only with an extensive understanding of human capabilities can he design machines to perform these functions. Further more, the human operator epitomizes the multipurpose adaptive black box, and a methodology for discovering and describing the characteristics of such systems with known inputs and outputs but unknown structure generalizes to other complex dynamic and control situations in the fields of physics, biology, economics, sociology, etc.

To be useful for engineering purposes, a model must predict the behavior of the system being modeled over a wide set of circumstances. What is sought is a single mathematical expression which specifies the output given the input. Accompanying the equation should be a set of rules which state how the parameters of the equation change as a function of task parameters-input, controlled element, environmental stresses, verbal instructions, etc.

1. The Continuous Closed-Loop Servomechanism Model

The simplest kind of manual-control task to analyze and model is continuous one-dimensional tracking, where the operator's problem is to make the output of the controlled process or vehicle (we shall call this continuous function of time $y(t)$) correspond as closely as possible to the displayed ideal or reference input $r(t)$. A simple mechanism to accomplish this task is a servomechanism, Figure 3.20, where a controller (in our case the human operator) observes and acts upon the error $e(t)$, equal to $r(t) - y(t)$, and drives the controlled process by means of one or another hand or foot control (we will call the control variable $u(t)$) to null or compensate for error. For this reason the task diagrammed in Figure 3.20 is called "compensatory" tracking. The human operator is labeled Y_H and the controlled process Y_C to indicate general dynamic operators on time functions to produce time functions.

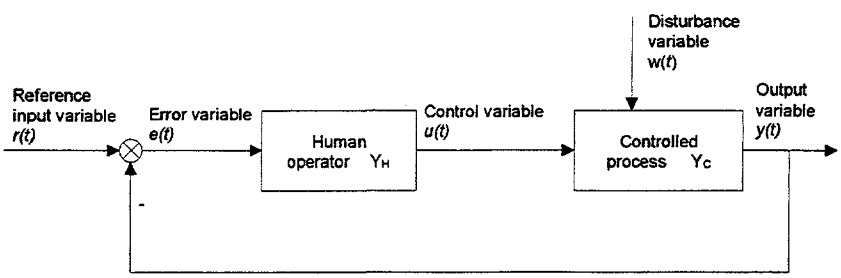


Figure 3.20 Simplified manual-control system

An unpredictable disturbance signal $\omega(t)$ is shown forcing the controlled process in Figure 3.20. Such a disturbance may enter the loop anywhere. Since both the magnitude and location of such spurious signals are usually unknown, but the servomechanism nevertheless compensates for them, they are frequently omitted.

2. Classes of Variables in Manual-Control Systems

Man's performance as a controller depends upon a great number of variables, properties of the particular 'situation" he finds himself in.

Some of these are called *task variables*: reference input signals and disturbance input signals; the dynamic process one is controlling; what and how information is displayed to the operator; and the control device or manipulator by which the operator acts on the controlled process. Feedback signals are normally used as task variable.

A second class of variables are the *environmental variables*, including such factors as additional tasks, vibration, ambient illumination, temperature, partial pressure of oxygen. These variables are closely related with environmental condition within the work place. We will discuss requirement for these variables in later chapter.

A third class includes *operator-centered variables*: such things as training, motivation, skill, fatigue.

Finally are the *procedural variables*, including instructions for the given task, order of presentation of trials and other features of an experimental design or measurement procedure, and the control criterion specifying the values of different trade-offs among objectives (the "payoff") and resources used (effort, time, errors).

3. Classification of closed loop manual-control system

Closed-loop manual-control systems can be classified according to the nature of the input to the human operator.

1. A *compensatory system* is one in which the human operator has a single input, the error e, the difference between actual system response y and ideal response (the reference input). The compensatory system is thus the equivalent of the one-dimensional servomechanism, Figure 3.20, in which the human's task is to null the instantaneous error without reference to absolute values of system output. Most models of the human operator assume a compensatory system.

2. A *pursuit system* (Figure 3.21) is one in which the instantaneous reference input r and instantaneous controlled process output y are both displayed to the human operator separately and independently, so that he may distinguish individual properties of these signals by direct observation. The human controller model must then be treated as a function of two input variables if the human behavior is linear, it may be considered as a sum of two functions, each of one variable, as it is in the figure. This is equivalent to an operation upon r and e, or upon e and y, since $e = r - y$ and there are only two degrees of freedom. But we will find that only with compensatory displays (where error is the displayed input, and r and y are not explicitly presented) or in compensatory models (where the model assumes a subtraction of y from r, so that the human operator is assumed to be a function of one variable) can the input-output characteristics be directly measured.

3. A *preview system* is similar to the pursuit system except that the human operator has available, a true display of $r(t)$ from the present time until some time into the future based on model of the expected future. Future time here refers to the time prior to when controller response to the corresponding segment of input is appropriate. If a whole future input trajectory is know, control be optimized by means of dynamic programming or some other modern control algorithm. Preview control is more characteristic of everyday tasks than pursuit or compensatory control.

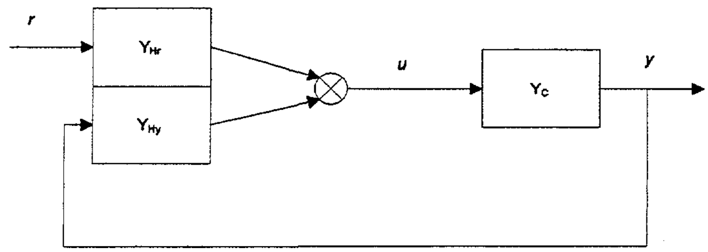


Figure 3.21 Pursuit system

4. A *precognitive system* is one in which the operator has foreknowledge of the input in terms other than a direct and true view. Precognition is a generic term referring to knowledge of statistical properties of the input which help the operator predict: knowledge of certain amplitude constraints (e.g., "the input will never get larger than so much"), knowledge of certain temporal constraints (e.g., "it's about time for another step") or contingency information (e.g., "that waveform is always followed by a sudden jump"). Precognition by the operator does not always result in better response to each feature of the input. For example, the range effect is presumably due to the operator's knowledge of the statistical range of inputs: he tries to minimize some average of error over responses sacrificing performance at extreme ranges to improve the average, or to make his response sooner. In any manual-control task the operator has some knowledge of the task variables.

4. The Quasi-Linear Controller Model

The simplest form of the human operator block in Figure 3.20 that gives realistic results is a constant-coefficient linear differential equation relating *u(t)* to the man's input, assumed w be *e(t)*. However, as we shall see in more detail, two expedient additions to the basic differential equation increase the descriptive power of the model.

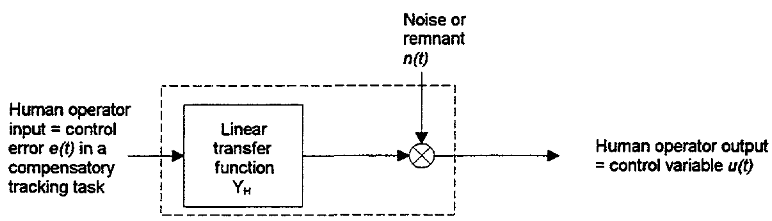


Figure 3.22 Quasi-linear human-operator model

The first assumes a generator of random noise or remnant within the human operator. The noise is added to the man's linearly determined output to model that residual component of response which cannot be described by a "best-fit" constant-coefficient linear differential equation. This is illustrated in Figure 3.22.

The second modeling expedient assumes that all the parameters of the human operator (linear differential equation and remnant generator) are constant so long as the task variables of the human operator's tracking situation (i.e., the reference input signal and the dynamics or the controlled process parameters) do not change. Thus, accompanying the structural statement of the model (form of equation plus noise generator) is a table of model

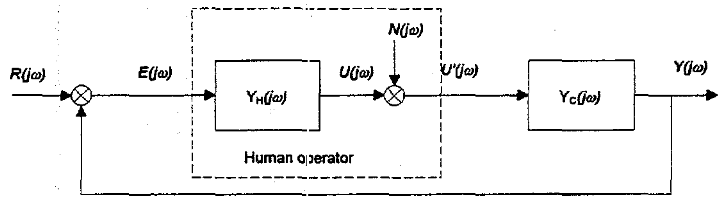


Figure 3.23 Fourier-transformed closed-loop human-operator system

parameters for significantly different situation parameters.

Clearly if parameters of the differential equation and remnant changed radically with modest changes of input or controlled process one would not have a good model; for the test of a good model is its relative - invariance over a wide range of applications.

Taken together, the constant-coefficient differential equation, the stationary noise or remnant generator, and the table of different "constant" parameters for different inputs and/or controlled processes constitute what is sometimes called a quasi-linear model.

McRuer and Krendel reviewed results of previous experiment, they found that the results could best be fitted by a model like that in Figure 3.23, i.e., a quasi-linear equation for the human operator of the form

$$U'(j\omega) = Y_H(j\omega)E(j\omega) + remnant \tag{3.1}$$

$$Y_H(j\omega) = \frac{K \exp\{-j\omega\tau_d\}\{T_L j\omega + 1\}}{(T_N j\omega + 1)(T_I j\omega + 1)} \tag{3.2}$$

K - loop gain adjustable by the operator, from 1 to 100

τ_d - reaction-time delay, between 0.12 second and 0.20 second

T_N - coefficient of the first-order lag inherent in the neuromuscular system, ~ 0.20 sec

T_L and T_I - lead and lag coefficients can be adjusted by human along with K

In the crossover region, a model that satisfies the criteria for a good servo is

$$Y_H Y_C \approx \frac{1}{j(\omega / \omega_C)} \tag{3.3}$$

5. Intuitively Modeling the Human Operator

If we were to start synthesizing a first-approximation linear model of the human operator, there are three properties intuition might suggest we include (Sheridan and Ferrell, 74):

1) *Reaction-time delay* Simple reaction-time experiments reveal a minimum reaction-time delay or refractory period 4 of about 0.15 seconds, which includes neural synaptic delays, nerve conduction time, and central processing time as well as the time necessary to make a just-measurable response. This manifests itself as a linear increase in phase with frequency.

2) *Gain* Any feedback control loop, in order to have reasonably fast response, would have a gain $K = |Y_H Y_C|$ as large as possible consistent with stability. The gain is dimensionless, and usually varies between 2 and 20 at low frequencies.

3) *Neuromuscular lag* Once a muscle is commanded to move, the muscle's inherent viscosity and inertia combined with the asynchrony of muscle fiber contraction might be expected to result in exponential response. It does this with a time constant t_n of 0.1 to 0.2 seconds.

Combining the above properties produces a model which can be written as

$$Y_H = \frac{K \exp\{-t_r j\omega\}}{1 + t_n j\omega} \qquad (3.4)$$

3.3.2.2 Extensions of Manual Control Theory toward SC

For the design of airplanes that can accurately and safely be flown by hand, knowledge of the control behavior of the entire man-machine system including that of the human operator, is essential. Therefore the engineer (the designer) should be able to model and predict the performance of the operator as a component of the man-machine system (Sheridan and Ferrell, 74).

Since roughly 1950 there has been much effort devoted to using conventional linear control theory to model simple manual control systems (Figure 3.24), where the human operator is the sole in-the-loop control element and the controlled process can be represented by linear differential equations.

A primary motivation for this work was the need to establish predictive models for control of aircraft, where having good differential equation models for the controlled process was of no use unless models of the pilot were factored in as well. Initially it was believed that an independent model of the pilot was appropriate, so that the pilot model could then be combined with whatever controlled process was of interest. This was soon found to be impractical, since the characteristics of the human operator proved to be very much dependent upon the controlled process, varying to compensate for the controlled process so as to stabilize the closed-loop system and provide satisfactory transient response.

It was then proposed to model the human operator and the controlled process as a single forward loop element. The idea was that there would be only minor variation of the combined human and process from application to application. This approach proved very successful. The result is the simple crossover model of McRuer *et al.*, the model will be introduced in the following sections.

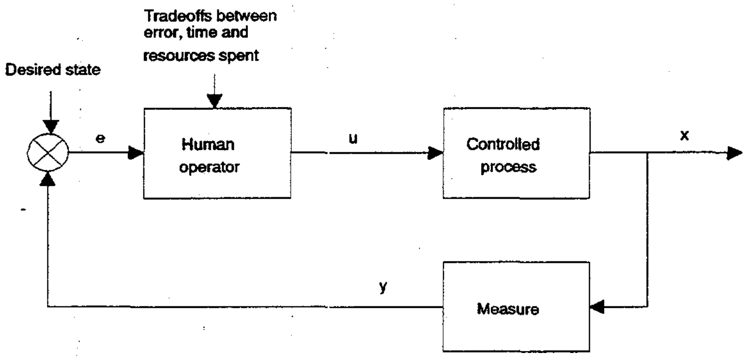


Figure 3.24 Simple compensatory manual control paradigm

1. McRuer Crossover Models

McRuer *et al.* reported further extensive measurements of the operator's describing function in a simple tracking task with a spring-centered control-stick. They employed both the continuous cross-power-spectral technique and the technique of measuring the describing function at discrete frequencies.

They sought to validate and extend the model in Equ. (3.2), and specifically chose forcing functions of sufficiently high bandwidth to permit critical tests of the operator's compensation for controlled-element response at these higher frequencies; they even tested some controlled elements whose dynamics were inherently unstable. Their forcing functions consisted of sums of sine waves, nonharmonically related and therefore random appearing, with frequency cutoff ωi at 1.5, 2.5, and 4.0 radians per second.

These inputs were combined with controlled elements K_C, $K_C\ /j\omega$, $K_C/(j\omega^{-2})$, $K_C\ /(j\omega)^2$, and $K_C/j\omega(j\omega\text{-}1/T)$, each used in turn with various values of controlled-element gain K_C. The experimenters were selective in combining conditions and iterating runs, since a complete factorial experiment would have been wasteful of effort. Nine test subjects, experienced test pilots, were required to practice with the laboratory apparatus until their performance (rms. error) reached a predetermined level. This typically required 10 to 20 minutes runs with each different controlled element.

2. The Simple Crossover Model

McRuer *et al.* found that for the most part their earlier quasi-linear model Equ. (3.2) could be suitably adjusted to fit their experimental results.

However, they found striking evidence that for a variety of forcing functions and controlled elements the slope of $|Y_H Y_C|$ vs. frequency was unit, i.e., - 20 dB(decade, in the region of the crossover frequency ω_C. Hence near ω_C the earlier model of Equ. (3.2) when combined with Y_C reduces to the much simpler form suggested by the "good" servo characteristics of Equ. (3.3).

$$Y_H Y_C \approx \frac{\omega_c \exp\{-j\omega\tau_\varepsilon\}}{j\omega} \qquad (3.5)$$

Here $Y_H Y_C$ is viewed as a combined open-loop transfer function (of argument j since the model is most valid in the frequency domain). This is exactly like the unity gain "good" se~o of (11.46) except for the exponential delay term. The two parameters of the model are defined as follows:

1. The crossover frequency ω_C is equivalent to the human operator's gain compensation. It can be modeled as a sum of hypothetical crossover frequency ω_{C0} for a forcing-function bandwidth ω_i equal to zero (i.e., a DC signal), where ω_{C0} varies only with controlled element Y_C plus an incremental crossover frequency $\Delta\omega_C$ which varies with forcing function bandwidth, or

$$\omega_c = \omega_{c0}(Y_C) + \Delta\omega(\omega_i) \qquad (3.6)$$

2. The effective time delay τ_ε is due to both reaction time and high-frequency neuromuscular dynamics. it is modeled as a delay to for a zero-bandwidth forcing function which varies with τ_ε plus an incremental time delay $\Delta\tau$ which varies with ω_i,

$$\tau_\varepsilon = \tau_0(Y_C) + \Delta\tau(\omega_i) \qquad (3.7)$$

3. Extended Crossover Model

McRuer et al. proposed several modifications to their simple crossover model to be used if a better fit to data is necessary. At low frequencies the data usually show a residual phase lag not accounted for by the simple crossover model. Closed-loop performance is not usually affected by this residual phase lag since $|Y_H Y_C|$ is large at low frequency.

The modified model is especially useful when the human operator is stabilizing an unstable controlled process, resulting in a low phase margin and requiring an accurate representation at midband frequencies short of crossover.

The form of the extended crossover model for Y_H alone is

$$Y_H = \frac{K_H(T_L j\omega + 1)\exp\{-j(\omega\tau_\varepsilon + \alpha / \omega)\}}{(T_I j\omega + 1)} \qquad (3.8)$$

The quantity a is the residual low-frequency phase-lag coefficient which increases (in the range 0.1 to 0.5 radians per second) with the order of Y_C and with increasing ωi. The dependence of α on task variables is not so well defined as for ω_i, and τ_ε. For $Y_C = K_C / j\omega(j\omega - 1/T)$ the product $\alpha\tau_\varepsilon$ was approximately constant at 0.11. Figures 11.6 and 11.7 illustrate how the extended crossover model provides a better fit at low frequencies than does the simple crossover model.

4. Applicable range for the Crossover Model

The crossover model permits the man-machine system engineer to predict how man-plus-machine will respond, given the controlled process Y_C and the bandwidth ω_i of the input *r(t)*. The available remnant model specifies just how accurate one may expect the prediction to be.

The range of parameters implied for Y_C and *r(t)* in the above discussion on crossover models accommodates many aircraft and other manned-vehicle control situations. However, for bandwidths greater than 10 rad/sec and for controlled processes which are sharply nonlinear or of high order and undamped (say $K_i(j\omega)^3$), or have more severely unstable poles than those discussed, the crossover model is invalid and indeed a human operator may be impracticable. Further, the crossover model is valid only for compensatory (error) tracking when the input is unpredictable.

Crossover models have been used in a variety of engineering and research applications. First, they have been used in a direct engineering sense to predict system response as a function of input and as a function of the parameters of the controlled process, assuming input, controlled process, and other conditions are within the range for which the model is valid. Thus the vehicle designer can say with some certainty how his vehicle will perform while it is still on the drawing board.

Second, in a less direct but perhaps more important sense, crossover models have been used as measuring instruments to determine the effects of a variety of conditions which are not explicit in the model. Some of these are psychophysiological, like heat stress, anoxia, operator training or motivation, cockpit lighting and displays, or operating procedures.

3.3.2.3 Optimal Control

1. Assumptions behind the Optimal-Control Approach

An optimal controller is one which, given a process to control, given constraints on the accuracy with which it may observe state variables, and given the energy or time it may use in controlling, acts to minimize some performance criterion or cost function in view of its own constraints. The criterion is usually stated as a linear quadratic function of error ($e = r - x$), control effort u, and possibly time (in transient control situations). The quadratic criterion function is used because:

(1) solutions are analytically tractable with quadratic criteria and

(2) what minimizes a quadratic criterion such as $J = \int \left[e^2(t) + u^2(t)\right] dt$ also minimizes a great many other "reasonable" criteria, such as $J = \int \left[|e(t)| + |u(t)|\right] dt$.

The idea of an optimal model is attractive. It assumes that the human operator, when sufficiently trained, is familiar with his own dynamics, with the controlled process dynamics, with the statistical nature of his own variability and that of the external disturbances, and with the criterion describing the best control, i.e. the tradeoff between error and control effort (and perhaps time, if the task is not steady state). Thus, if the human operator is intelligent, it is plausible that he will attempt to behave optimally to the best of his ability to perceive and remember signals and produce the best control responses.

Assuming that optimal control for the given controlled process and criterion function can be specified, we may then measure human behavior by deviation from this ideal. Often the optimal-control model will include certain free parameters which may be adjusted to provide a best fit to empirical data, and by fitting the data one says, in effect, "if the data are from an optimal controller with respect to the given criterion, then the constraining parameters are most likely to have the following values."

2. Synthesising Optimal Regulators

In the simple case where u is a scalar sum of weighted state variables

$$u = -\mathbf{l}^T\mathbf{x} \tag{3.9}$$

where the superscript T represents the vector transpose and **x** is directly observable, the components of **l** can be adjusted to make the poles of the characteristic equation of the closed-loop system fall wherever desired. This is as in traditional control theory where one uses derivatives of various order as feedback to give the system good properties. For the undamped harmonic-oscillator example above, given feedback of the state variables x_1 and x_2, we have

$$u = -l_1x_1 - l_2x_2 \tag{3.10}$$

where $x_1 = z$ and $x_2 = \dot{z}$; hence

$$\ddot{z} = -\omega_0^{\,2}z - l_1z - l_2\dot{z} \tag{3.11}$$

or

$$\ddot{z} + l_2\dot{z} + (\omega_0^{\,2} + l_1)z = 0 \tag{3.12}$$

The characteristic equation will be

$$\lambda^2 + l_2\lambda + (\omega_0^{\,2} + l_1) = 0 \tag{3.13}$$

where l_1 and l_2 can be adjusted to yield the desired behavior, according to any criterion of desirability, as might be supposed from the fact that l_2 determines the -damping ratio and l_1 the natural frequency.

A common way of determining the controller gain matrix **L** (or vector l in our present example using a scalar **u**) is to have it minimize an integral quadratic function of **x** and a vector **u**. Such a function is called a criterion or cost functional J:

$$J(\mathbf{u}) = \frac{1}{T}\int_0^T (\mathbf{x}^T\mathbf{Q}\mathbf{x} + \mathbf{u}^T\mathbf{R}\mathbf{u})\,dt \tag{3.14}$$

The above scheme requires measuring all of the state variables explicitly, which is not usually possible. Another approach is to reconstruct the state variables by feeding u(t) into a model of the controlled process. For this approach we write

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} + \mathbf{B}\mathbf{u} \tag{3.15}$$

There ^ signifies an estimated or modeled variable and $\mathbf{x}(t_0)$ must also be known. This open-loop reconstructor is fine if **A**, **B**, **u**, and $\mathbf{x}(t_0)$ are known exactly. Better still would be to feed any discrepancy between $\mathbf{x}$ and $\hat{\mathbf{x}}$ back into our reconstruction equation. The closed-loop reconstructor is formed by adding to the open-loop reconstructor an operation on $(\mathbf{x}-\hat{\mathbf{x}})$. Since, as we mentioned, $\mathbf{y} = \mathbf{C}\mathbf{x}$ may be the best measure we have of $\mathbf{x}$, this will, in general, take the form of an operation $\mathbf{G}$ on $\mathbf{C}(\mathbf{x}-\hat{\mathbf{x}})$ thus:

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} - \mathbf{B}\mathbf{u} + \mathbf{G}\mathbf{C}(\mathbf{x}-\hat{\mathbf{x}}) \tag{3.16}$$

By subtracting the basic state equation $\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t)$ from this equation there results

$$(\dot{\hat{\mathbf{x}}} - \dot{\mathbf{x}}) = \mathbf{A}(\hat{\mathbf{x}} - \mathbf{x}) - \mathbf{G}\mathbf{C}(\hat{\mathbf{x}} - \mathbf{x}) = [\mathbf{A} - \mathbf{G}\mathbf{C}](\hat{\mathbf{x}} - \mathbf{x}) \tag{3.17}$$

The n components of G can now be chosen to make this equation stable with negative real roots so that

$$(\hat{\mathbf{x}} - \mathbf{x}) \to 0 \text{ and } (\dot{\hat{\mathbf{x}}} - \dot{\mathbf{x}}) \to 0 \text{ as } t \to \infty \tag{3.18}$$

A reconstruction filter of this sort is also called an observer. Various procedures for finding satisfactory values for the elements of G are given in the references.

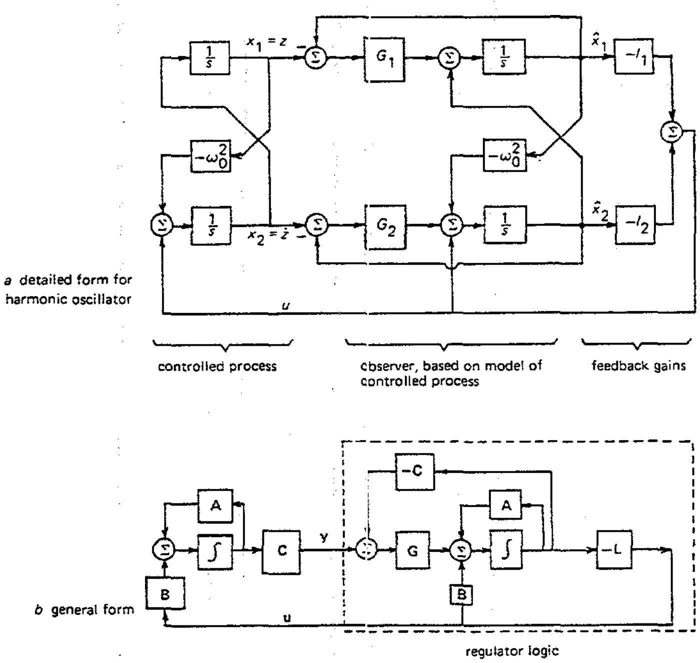


Figure 3.25 Reconstructed state-variable feedback for a simple harmonic oscillator

Combining the two ideas above, we use for the control vector in the general case

$$\mathbf{u} = -\mathbf{L}\hat{\mathbf{x}} \tag{3.19}$$

This is diagrammed for the simple harmonic oscillator in Figure 3.25a and in the more general form in Figure 3.25b. There are two sets of roots of the system of Figure 3.25, one set being the roots of the observer [**A** - **GC**], the other set -being the roots of the controlled process with direct state-variable feedback control [**A** - **BL**]. The fourth-order characteristic equation of the harmonic-oscillator control system diagrammed in Figure 3.25a thus factors into two second-order equations, or

$$\left[\lambda^2 + l_2\lambda + (\omega_0^2 + l_1)\right]\left[\lambda^2 + G_1\lambda + (\omega_0^2 + G_2)\right] = 0 \tag{3.20}$$

This remarkable ability to separate observer and feedback gains allows these elements to be designed separately. These techniques are presented here in a form adapted from Bryson and Luenberger (70), only to introduce the concepts.

The systems considered above were completely deterministic. Fortunately for application to real systems controlled by people, these techniques can be extended to time-invariant linear systems plus noise of the form

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{v}(t) \tag{3.21}$$

where the noise v(t) is a vector function of zero mean, Gaussian amplitude distribution, is white (i.e. has equal energy at all frequencies), and is characterized by its covariance matrix V. Fortunately the estimation of x in this case follows much the same procedure as the deterministic reconstruction outlined above. In this noisy case J is taken as an expected value of the integral quadratic form of Equation (3.14). Then a known result, which we cannot derive here, is that J is minimized when

$$\mathbf{u}(t) = -\mathbf{R}^{-1}\mathbf{B}^T\mathbf{K}\mathbf{x}(t) \tag{3.22}$$

(often written as - L*x, a convention to express optimum feedback control), where the constant matrix **K** is the unique positive-definite solution of the algebraic Riccati equation:

$$\mathbf{KA} + \mathbf{A}^T\mathbf{K} + \mathbf{Q} - \mathbf{KBR}^{-1}\mathbf{B}^T\mathbf{K} = 0 \tag{3.23}$$

The above analysis can be extended to the case of "colored noise," where white noise is assumed to be filtered to produce the given noise, but the required filter is treated as part of the given dynamic process and the state variable set is enlarged accordingly. One may also treat time variable dynamic systems by related techniques.

3. Kalman filter and optimal control

A second widely accepted class of models of direct manual control (Figure 3.26) is based on so-called optimal or modern control theory. Inherent in such models is the use of a model based controller, which in turn contains a model-based state-estimator (observer, or Kalman filter) to provide an optimal estimate of controlled process state variables. Once true state variables are known, there are well-established control laws for forcing the controlled process in order to minimize some criterion-for example, some function of state variable deviation from the desired state (control error) and resources expended (control action). In most real-world cases, true state variables are not available or not known precisely and must be estimated on the basis of current (noisy) measurements and on basis of the effect of past control inputs on the process (to the extent that the process dynamics are known).

If state variables can be accurately measured, then control is relatively straightforward by traditional means. If, by contrast, one has a perfect model of the controlled process and there is negligible disturbance, one need not bother to measure state.

Knowing the past and present inputs to the process allows precise determination of the state; control can be "open-loop". Seldom is either condition true. One must use both noisy state measures and the best available model. The Kalman filter is a way to combine information from both.

The configurations of the model-based controller, and the estimator or Kalman filter itself though well known to control engineers, are shown in Figure 3.26 for the benefit of those not familiar with these ideas. **A**, **B**, and **C** represent the gain matrices that shape the actual vector variables for state feedback in the controlled process, for control, and for measurement as shown in the figure. **A'**, **B'**, and **C'** are the best available *models* of these, and, together with knowledge of the disturbance statistics, the observation noise statistics, and the known deterministic inputs, constitute an *internal model* of the external reality that is the heart of the Kalman filter. The modeled output measurement vector **g** is compared against the actual measurement **y**, and the discrepancy or residual **g** is used for a continual Bayesian correction from prior to posterior estimate * of state **x**.

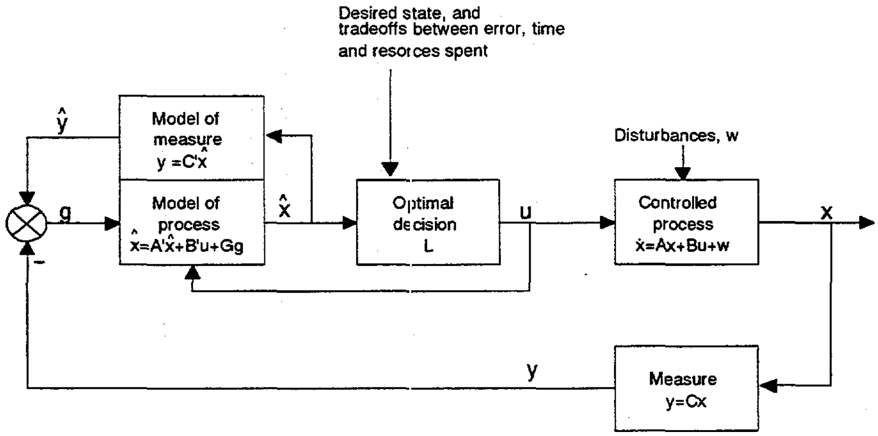


Figure 3.26 Modern (optimal) control paradigm, using Kalman filter

Roughly speaking, this correction (the *Kalman filter gain)* is made proportional to **g**, proportional to confidence in the previous measurement (more confident the smaller the observation noise covariance), and inversely proportional to confidence in the *a priori* state estimate (more confident the smaller the state-variable error covariance). We shall see later that the Kalman residual is useful not only as a correction factor but also as an indication of a process actively deviating from what was supposed to be-in other words, for failure detection.

This approach produces a minimum variance state estimate with white noise residuals if one assumes that the controlled process is linear, that its internal model matches the actual process effectively, and that noise terms are Gaussian and random. With such a "best" estimate of state, the control law L can perform its criterion-minimizing function independently of the estimation. Again, it is not the purpose of this book to provide a tutorial on modern estimation and control, but to provide some idea of the basis for some important models of supervisory control. The general and powerful idea of an internal model will be referred to again below.

Baron comments that a model based on the Kalman filter estimator can become so confident of its prior state estimates (based on the model) that it virtually operates in open-loop fashion and ignores exteroceptive feedback for short periods. He suggests, and the present author agrees, that such behavior is often observed in human operators.

4. The Baron-Kleinman-Levison Model

Based upon the above introduction we can present the Baron-Keinman-Levison model of the human as an optimal controller. Their basic assumption is that the well-trained, well-motivated human operator will act in a near-optimal manner, subject to certain internal constraints which limit his behavior and also subject to the extent to which he understands the task objectives.

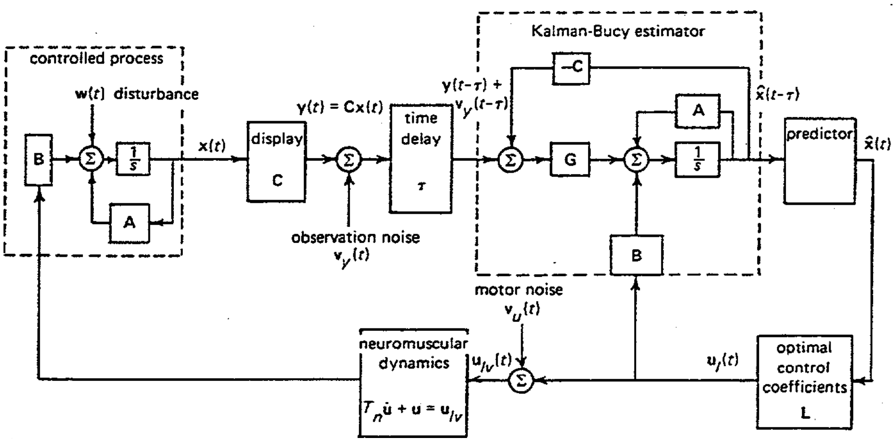


Figure 3.27 Baron-Kleinman-Levison Optiman control model

Baron *et al.* assume a linear time-invariant system with noise as in Equation (3.21), and a quadratic cost functional of the form of Equation (3.14). But they use $\dot{u}$ instead of u because, with significant neuromuscular lag parameter T_N, a scalar a is what is voluntarily forced to produce u. It is presumably what the human operator perceives, and represents a subjective penalty on rapid control movements. Their model is shown in general structural form in Figure 3.27 (Kleinman and Baron, 71).

They further assume the human operator to be monitoring an instrument panel, and that, as a function of how he scans or samples the displayed variables, there is an additive observational noise $v_y(t)$ (white and Gaussian with covariance V_y). There is also a pure time delay r somewhere in the human operator which for convenience is put at the input.

The controller L in the Baron-Kleinman-Levison model is determined by the solution to the "optimal regulator" problem as given by Equations (3.9) to (3.23) but with added motor noise v_u (covariance V_u) and a neuromuscular first-order exponential lag with time constant T_N resulting from the control-rate weighting assumption. Baron *et al.* include a linear dynamic estimator of state like the closed-loop estimator described above, but in a special form called a Kalman-Bucy filter. This filter accommodates to the process disturbance $\omega(t)$ and measurement noise $v_y(t)$ by having gains L set to minimize the mean-square error of the estimates. To this, in their model, they cascade an additional element which gives a prediction of $\mathbf{x}(t)$ in a least-mean-square-error sense, which we call $\hat{\mathbf{x}}(t)$. This models the human's tendency to anticipate and compensate for his own time delay.

Thus, we are given the parameters of the controlled process **A** and **B** and the independent input or disturbance $\omega(t)$ and the properties of the explicit criterion function *J*, i.e., the **Q** and **R** weightings. When u is a scalar, **Q** reduces to a set of coefficients q_i and **R** reduces to a single coefficient.

To calculate the parameters of the model one starts with values for T, T_N, V_y/σ_y^2, and V_u/σ_u^2, where the last two terms are noise-to-signal power ratios for input and control output respectively. From these and the task parameters given above the coefficients of the other elements of the optimal regulator can be determined.

5. Problems in Using Optimal-Control Models

Optimal-control models of the human operator have proven successful. However they present several problems which are difficult from the viewpoint of the theory of modeling.

One is never quite sure what the experimental subject's internal subjective criterion is. Moreover, optimality with respect to one criterion and with one set of time constants and noise parameters can be almost exactly the same as optimality with respect to another criterion and with another set-of time constants and noise parameters. If the subject is asked to minimize a given objective criterion function, he may invoke a different subjective criterion function and be quite optimal with respect to the latter, and be precisely optimal with respect to a criterion of which neither he nor the experimenter is aware. All one can really do to cope with this limit on certainty is to use (or assume) criteria which seem "natural" and rely on plausibility arguments. More research on this subject is needed.

It is important to recall that the optimal-control model is merely a means of predicting output from input and need make no assumptions about whether the human operator has inherent rules for how to become optimal or even for deciding what optimality is. Indeed, given a chance to practice with (i.e., get feedback from) an explicit criterion function, he may acquire his optimality by simple operand conditioning according to Skinner's theories of learning. Thus one could converge on optimality by responding successively in trial-and-error fashion to get better and better scores, with no explicit understanding of the criterion. Both experience and common sense, however, suggest that some intellectual understanding improves performance and accelerates learning.

The optimal-control model is capable of handling relatively complex multivariable systems, so long as they are linear, and it has great potential here. Multi-input sampling behavior and situations in which the controlled process has time-varying parameters, are studied. Most of the underwater operations require nonlinear control, nonlinear optimal control has yet to be applied to human-operator modeling to any significant extent and remains a formidable theoretical area. The possibility of integration of human-operator into the underwater control system dynamic model needs to be investigated.

4 Evaluation of underwater control system

4.1 Evaluation methodology

4.1.1 Definition of evaluation method

An evaluation is meant to determine the "value", "usefulness" or "strength" of a solution with respect to a given objective. An objective is indispensable since the value of a solution is not absolute, but must be gauged in terms of certain requirements. Ullman (92) defines that an evaluation involves a comparison of concept variants or, in the case of a comparison with an imaginary ideal solution, a "rating" or degree of approximation to that ideal.

An important element of design practice is cost analysis. It involves value analysis, that is, the determination of "function costs", by the assignment of function carriers to the various sub-functions, and the determination of their manufacturing costs. The main problem here is to several sub-functions or a single function may be fulfilled by several components, which leads to an ambiguous distribution of costs. Moreover, costing presupposes the availability of considerable design documentation. Finally, if the evaluation and choice of solutions are based purely on production costs, there is a danger that essential technical criteria and other economical considerations will be ignored. For instance the market reaction to a product cannot be quantified in terms of money.

Hence there is a need for methods that allow a more comprehensive evaluation, or in other words cover a range of objectives (task-specific requirement and general constraints). These methods are intended to elaborate not only the quantitative, but also the qualitative, properties of the variants, thus making it possible to apply them during the conceptual phase. The result must be reliable, cost-effective, easily understood and reproducible.

4.1.2 Purpose of product concept design evaluation

Evaluation, as used in this text, implies both comparison and decision making. These are tightly interrelated actions. In order to have enough information to make a decision on the development potential of a concept or a product, they must be compared with something else. To make the comparison, the concepts to be compared must be couched in the same language and they must exist at the same level of abstraction.

In this chapter a methodology will be developed that will help in making a knowledgeable decision with limited information. This methodology uses four techniques to reduce the many concepts generated to the few concepts most promising for development into a quality product. The techniques, presented in the boxes in Figure 4.1, are the topics of the sections of this chapter.

An additional problem with concept evaluation is that abstract concepts are fuzzy; as they are refined their behavior can differ from that initially anticipated. The greater the knowledge one has about a concept, the fewer surprises one get. However, even in a well-known area, as the concept is refined to the product, unanticipated factors arise.

There are two possible types of comparisons. The first type is absolute in that the concept is directly compared with some set of requirements. The second type of comparison is relative in that the concepts are compared with each other. As shown in Figure 4.1, the first three comparison techniques, all absolute, are used as a filter for the relative comparison technique calls a decision matrix.

The goals of evaluation are:

- manage the functional development of the product and
- gather enough information to compare the product design with the targets set for the engineering requirements.

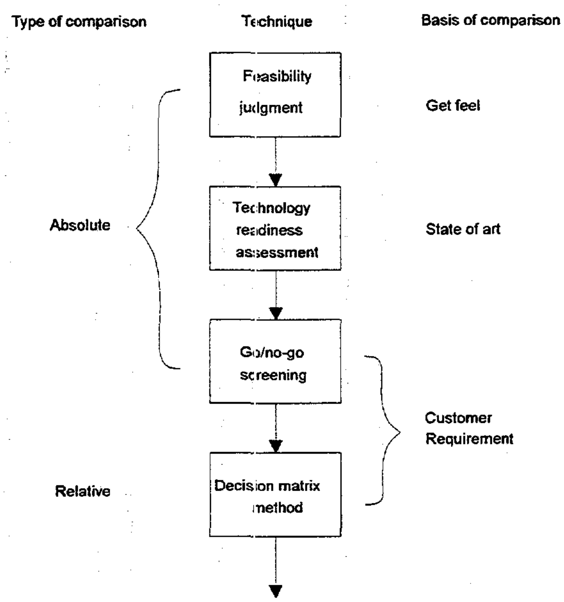


Figure 4.1 Concept evaluation techniques

Product evaluation includes (Figure 4.2):

- Functional evaluation
- Performance evaluation
    - Analytical model development
    - Graphical model development
    - Physical model development
- Evaluation of costs
- Designing for assembly
- Designing for the "illities"
    - Reliability and failure analysis

- Testability
- Maintainability
- Ergonomic evaluation

4.1.2.1 The goals of functional evaluation

Although the main goal of evaluation is comparing the product design with the engineering targets, it is equally important to track changes made in the function of the product. Conceptual designs were developed first by functionally modeling the problem and then, based on that model, developing potential concepts to fulfill these functions. This transformation from function to concept does not end the usefulness of the functional modeling tool. As the form is refined from concept to product, so too is the function refined. Besides tracking the functional evaluation of the product, the refinement of the functional decomposition also aids in the evaluation of potential failure modes.

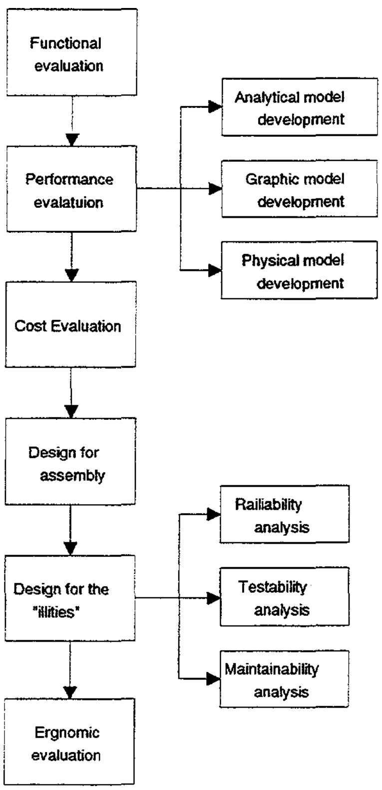


Figure 4.2 Steps of product evaluation

4.1.2.2 The goals of performance evaluation

The engineering requirements are developed through the concept generation phase. For each of these requirements, a specific target was set. The goal now is to evaluate the product design relative to these targets. Since the targets are represented as numerical values, the evaluation can only occur after the product is refined to the point that numerical engineering measure can be made. The sequence of techniques used for concept evaluation is also useful in product evaluation; however, the list must be expanded to include direct comparison with the engineering requirement.

The goal of product performance evaluation is to ensure that the product design generated will meet the engineering requirements. Additionally, effective evaluation procedures should clearly show what must be improved to make deficient designs meet the requirements and demonstrate the product's insensitivity to variation in the manufacturing process and operating environment. We will restate these goals with a little more detail. The evaluation of product performance must:

1. Result in numerical measures of the product for comparison with the engineering requirements' targets developed during problem understanding phase. These measurements must be of sufficient accuracy and precision for the comparison to be valid.
2. Give some indication about which features of the product design to modify, and by how much, to bring the performance on target.
3. Include the influence of manufacturing variations, aging effect, and environmental changes. Insensitivity to these "noises" while meeting the engineering requirement target results in a quality design.

4.2 Procedures of an evaluation process

The process of evaluation consists four main steps, choose of criteria, dimension of criteria, scale of criteria and weighing evaluation criteria. The most important step is to find the proper criteria for this problem, see Figure 4.3.

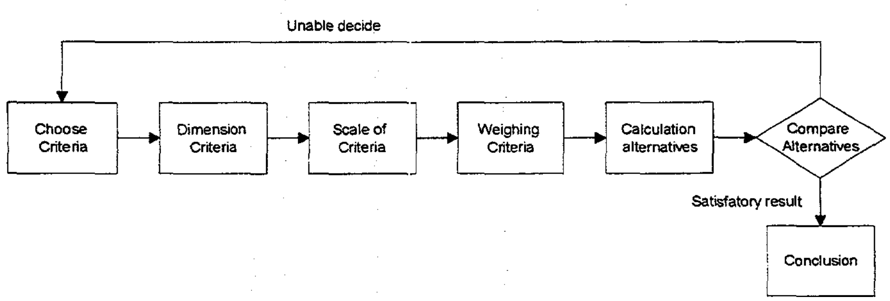


Figure 4.3 Steps in evaluation process

4.2.1 Principle for choice of criteria

The choice of criteria by which to judge alternative designs, systems, products, processes, and so on, is one of the most important tasks in multiple criteria decision making.

These general observations regarding the criteria used to discriminate among alternatives can immediately be made:

(1) each criterion distinguishes at least two alternatives, in no case should identical values for an criterion apply to all alternatives

(2) each criterion captures a unique dimension or facet of the decision problem (i.e., criteria are independent and non-redundant)

(3) all criteria, in a collective sense, are assumed to be sufficient for purposes of selecting the least alternative; and

(4) differences in values assigned to each criterion are presumed to be meaningful in distinguishing among feasible alternatives.

In practice, selection of a set of attributes is usually the result of group consensus, and it is clearly a subjective process. The final list of attributes, both monetary and nonmonetary, is therefore heavily influenced by the decision problem at hand. It has also an intuitive feel for which criteria will pinpoint relevant differences among feasible alternatives. If too many attributes are chosen, the analysis will become unwieldy and difficult to manage. Too few attributes, on the other hand, will limit discrimination among alternatives. Again, judgment is required to decide what number is "too few" or "too many." If some criteria in the final list lack specificity and/or cannot be quantified, it will be necessary to subdivide them into lower level criteria that can be measured.

4.2.1.1 Identifying evaluation criteria

The first step in any evaluation is the drawing up of a set of objective from which evaluation criteria can be derived. In the technical field, such objectives are mainly based on the requirements of the specification and on the general constraints.

A set of objectives usually comprises several elements that not only introduce a variety of technical, economic and safety factors, but that also differ greatly in importance.

A range of objectives should satisfy the following conditions:

- The objectives must cover the decision-relevant requirements and general constraints as completely as possible, so that no essential criteria are ignored.
- The individual objectives should be as independent of one another as possible; that is, provisions to increase the value of one variant with respect to one objective must not influence its values with respect to the other objectives.
- The properties of the system to be evaluated must, if possible, be expressed in concrete quantitative or at least qualitative (verbal) terms.

The population of such objectives depends very much on the purpose of the particular evaluation-that is, on the design phase and the relative novelty of the product.

Evaluation criteria can be derived directly from the objectives. Because of the subsequent assignment of values, all criteria must first be given a positive formulation.

Use-value analysis systematizes this step by means of an objective's tree, in which the individual objectives are arranged in hierarchic order. The sub-objectives are arranged vertically into levels of decreasing complexity, and horizontally into objective areas-for instance, technical, economical or even into major and minor objectives. Because of the required independence, sub-objective of a higher level may only be connected with an objective of the next lower level. This hierarchical order helps the designer to determine whether all decision-relevant sub-objectives have been covered. Moreover, it simplifies the assessment of the relative importance of the sub-objectives. The evaluation criteria, can then be derived from the sub-objectives of the stage with the lowest complexity.

4.2.1.2 Dimensioning the decision problem

This first way of dealing with data such as that shown in Table 4.1 is called single dimensioned analysis. (The dimension corresponds to the number of metrics used to represent the criteria that discriminate among alternatives.). Collapsing all information to a single dimension is popular in practice because many analysts and decision makers believe that a complex problem can be made tractable in this manner. Such models are termed compensatory because changes in values of a particular attribute can be offset by, or traded off against, opposing changes in another attribute (Sullivan, Canada, 92).

A second basic way to process information in Table 4.1 is to retain the individuality of the criteria as the best alternative is being determined. That is, there is no attempt to collapse attributes to a common scale. This is referred to as full dimensioned analysis of the multiple-criteria decision problem. For example, if r^* attributes have been chosen to characterize the alternatives under consideration, the predicted values for all r^* attributes are considered in the choice. If a metric is common to more than one attribute as in Table 4.1, we have an intermediate dimensioned problem that is analyzed with the same models as a full dimensioned problem would be. Several of those models are illustrated in the next section, and they are of ten most helpful in screening inferior alternatives from the analysis. We refer to these models as noncompensatory because trade-offs among criteria are not permissible. Thus, comparisons of alternatives must be judged on an attribute-by-attribute basis.

4.2.1.3 Selection of a measurement scale

Identifying feasible alternatives and appropriate attributes represents a large portion of the work associated with multiple-criteria decision making. The next task is to develop metrics (measurement scale or descriptors) that permit various states of each criterion to be represented. A subjective assessment of flexibility was made on a metric having five gradations that ranged from "poor" to "excellent". The gradations were poor, fair, good, very good, and excellent. In many problems, the metric is simply the scale upon which a physical measurement is made. For instance, anticipated noise level for various sound isolation materials to an equipment might be a relevant criterion whose metric is "decibels".

4.2.1.4 Weighing evaluation criteria

To establish evaluation criteria, we must first assess their relative contribution(weighing) to the overall value of the solution, so that relatively unimportant criteria can be eliminated before the evaluation proper begins. The evaluation criteria retained are give "weighing factors" which must be taken into consideration during the subsequent evaluation step. A weighing factor is a real positive number. It indicates the relative importance of a particular evaluation criterion (objective).

It has been suggested that such weighing should also be assigned to the wishes, recorded in the specification. That is only possible if such wishes can be ranked in order of importance when the specification is the first drawn up. However, evaluation criteria emerges during the development of the solution, and their relative importance changes

In use-value analysis, weighing are based on factors ranging from 0 to 1 (or from 0 to 100). The sum of the factors of all evaluation criteria(sub-objective at the lowest stage) must be equal to 1 (or 100) so that a percentage weighing can be attached to all the sub-objective.

Keeping in mind, a task such as weighing of criteria demands personnel with both a lot of experience and insight of the system concerned, otherwise, the chosen weighing factors may make no sense.

4.3 Methods of Evaluation

Traditional analyses do not account for the many intangible benefits that can be attained from complex systems. Multiple criteria decision making incorporates both quantitative and qualitative information into the decision-making process. Several useful methods for performing multiple criteria decision making for our application have been presented in this section.

4.3.1 Evaluation technique classification

4.3.1.1 Evaluation based on feasibility judgment

As a conceptual design is generated, the designer has one of three immediate reactions: (1) it is not feasible, it will never work; (2) it might work if something else happens; (3) it looks worth considering. These judgments about a concept's feasibility are based on "get feeling", a comparison made to prior experience stored as design knowledge. Let us consider the implication of each of the possible initial reactions more closely.

1) It is not feasible.

If a concept looks not feasible, unworkable or not fulfills the basic requirement, it should be considered briefly from different viewpoints before being rejected. Before discarding an idea, it is important to ask, "Why is it not feasible?" There may be many reasons. It may be obviously technologically not feasible. It may obviously not meet the customer's requirements. It may just be that the concept is different from the way in which things are normally done. Or it may be that because the concept is not an original idea there is no enthusiasm for it. We will delay discussing the first two reasons until the following sections; we will discuss the second two here.

As for the judgment that a concept is "different", because human has a natural tendency to prefer tradition to change, so an individual designer or company is more likely to reject new ideas in favor of those that are already established. This is not all bad because the traditional concepts have been proven to work. However, this view can block product improvement, and care must be taken to differentiate between a potentially positive change and a poor concept. Part of a company's tradition lies in its standards. Standards must be both followed and questioned; they are helpful in giving current engineering practice, but they also may be limiting in that they are based on dated information.

As for the judgment that a concept was "not invented here": It is a question of self-satisfying to individuals and companies to use their own ideas, even ideas borrowed from others are sometimes better.

A final reason to further consider ideas that at first do not seem feasible is that they may give new insight to the problem. Part of the brainstorming technique introduced in the last chapter was to build from the wild ideas that were generated. Before discarding a concept, see if new ideas can be generated from it, effectively iterating from evaluation back to concept generation.

2) It is conditional

The initial reaction might be to judge a concept workable if something else happens. Typical of other factors involved are the readiness of technology, the possibility of obtaining currently unavailable information, or the development of some other part of the product.

3) It is worth considering

The hardest concept to evaluate is a concept where it is not immediately evident whether it is a good idea or not, but it looks worth considering. Evaluation of such a concept is where engineering knowledge and experience are essential. If sufficient knowledge is not immediately available for the evaluation, then it must be developed. This is accomplished by developing models that can be easily evaluated. Considering the languages of design, there are essentially three classes of modeling for evaluation: graphical, physical, and analytical.

At this stage, it is important that we do not try to find out what is the best. So even we thought we have found a concept seems very good, we shall still put this concept into the class "Worth considering" for further evaluation. Because many of the "very good" concepts are the ones we are familiar with, if we decided that is the best, then we have reduced the chance to find a good "new" alternative.

4.3.1.2 Evaluation based on technology-readiness assessment

The second evaluation technique is to determine the readiness of the technologies that may be used in the concept. This technique refines the evaluation by forcing an absolute comparison with state-of-the-art capabilities. If a technology is to be used as a part of product design, it must be mature enough that its use is a design issue, not a research issue. The vast majority of technologies used in products are mature and the measures below are readily met. However, in a competitive environment, there are high incentives to include new technologies in products. An attempt to design a product before the necessary technologies are ready often leads either to a low-quality product or to a project that is terminated before a product reaches the marketed, because it is behind schedule and over cost. How then can the maturity of a technology be measured?

Six measures can be applied to determine a technology's maturity:

1) Can the technology be manufactured with known processes? If reliable manufacturing processes have not been refined for the technology, then either the technology should not be used or there must be a separate program for developing the manufacturing capability.

2) Are the critical parameters that control the function identified? Every design concept has certain parameters that are critical to its proper operation.
3) Are the safe operating latitude and sensitivity of the parameters known? In refining a concept to a product, the actual values of the parameters may have to be varied to achieve the desired performance or to improve manufacturability.
4) Have the failure modes been identified? Every type of system has characteristic failure modes. It is, in general, a useful design technique to continuously evaluate the different was a product might fail.
5) Does hardware exist that demonstrates positive answers to the above four questions? The most crucial measure of a technology's readiness is its prior use in a laboratory model or another product.

Is the technology controllable throughout the product's life cycle? This question addresses the latter stages of the product life cycle: its manufacture, service, and retirement. It also raises other questions. What manufacturing by-products come from using this technology? Are the by-products disposable in a safe manner?

4.3.1.3 Evaluation based on comparison

1. Go/no-go screening method

One technique, called Go/No-go screening technique, has been used for evaluation of some of mature concepts, the criteria used in decision are from customer requirements. That means each customer requirement must be transformed into a question to be addressed to each concept. The questions should be answerable as either *yes* or *maybe* (go), or *no* (no-go).

This type of evaluation will not only eliminate designs that should not be further considered, but will also help generate new ideas. If a concept has only a few no-go responses, then it may be worth modifying rather than being eliminated. This evaluation rapidly points out the weak areas in a concept so that it can be modified to fix the problem. (Ullman, 92)

2. Decision-matrix method

The decision-matrix method which is fairly simple, has proven very effective for comparing concepts that are not refined enough for direct comparison with the engineering requirements. The method provides a means of scoring each concept relative to another in its ability to meet the customer requirements. Comparison of the scores thus developed then give insight to the best alternatives and good information for making decision.

We will introduce a few techniques about weighing factor calculation and way of applying this method.

4.3.2 Noncompensatory sequential elimination methods

Sequential elimination methods were first categorized by MacCrimmon. They are decision rules (some times arbitrary) whereby an individual might be able to eliminate one or more alternatives to narrow the choice and perhaps even be led to a final decision.

These methods are applicable when one can specify values (outcomes) for all criteria and alternatives Those values should be scalar (measurable) or at least ordinal (rank orderable). The methods do not consider weighing, if any, of attributes.

Table 4.1 illustrates an example showing outcomes (values) for four attributes and four alternatives. Note the two right-hand columns state the "ideal" and the "standard (minimum acceptable)" values for each attribute.

One of the method among Noncompensatory sequential elimination methods is to eliminate all the alternatives that have at least one attribute is not qualified. In the example in Table 4.1, we can easily find out just by looking the table, Alternative 2,3,4 are disqualified by at least one attribute. Only Alternative 1 meets all the attributes, which is the one we choose.

Elimination methods are good for simple case with small number of attributes and very obvious result. These methods are very good in evaluating of those criteria marked "Must", but not very those marked with "Nice to have" or "May". For more complicated cases, however, since these methods do not consider trade-offs between alternatives, sometimes it is not possible to find an alternative fulfill the requirement.

Table 4.1 Example Multi-attribute problem used for Elimination method

Attribute	Estimated Outcome for alternative				Ideal	Standard (Minimum Accetable)
	1	2	3	4		
A. Quality	75	90	80	60	100	70
B. Flexibility	Very good	Good	Poor	Excellent	Excellent	Fair
C. Serviceability	50	38	35	30	50	30
D. Cost savings	8	6	5	6	10	7

In appendix, we present some other elimination methods, there we have a little more detailed illustration of those methods.

4.3.3 Evaluation based on weighing of attributes

4.3.3.1 Formula methods for weighing factor

Many numerical formula methods for assigning weights exist that are easy to use but generally less defensible than direct assignment of weights based on preference comparisons among criteria. Several of these formula-based methods are described by Sullivan and Canada(92). One example of calculation is shown in Table 4.2 for the same five criteria (attributes) given in Table 4.3 to illustrate this method. The weights are expressed as percentages.

Table 4.2 Example with four alternatives and five attributes

Attribute	Alternatives			
	P-1	P-2	P-3	P-4
A. Machine performance	Average	Above average	Average	Below average
B. Cost	350kNOK	300kNOK	280kNok	380kNOK
C. Serviceability	< 1 hr	1 - 1½ hr	1 - 1½ hr	1½ - 2 hr
D. Management/engineering effort	500 hr	700 hr	1100 hr	700 hr
E. Riskiness, lack of	Above average	Average	Below average	Average

1. Uniform or equal weights.

Given N attributes, the weight for each is

$$W_i = \left(\frac{1}{N}\right) \times 100\% \qquad (4.1)$$

2. Rank sum weights.

If R_i is the rank position of attribute i (with I the biggest rank, etc.) and there

$$W_i = \frac{N - R_i + 1}{\sum_{i=1}^{N}(N - R_i + 1)} \times 100\% \qquad (4.2)$$

are N attributes, rank sum weights, W for each attribute, may be calculated as

3. Rank reciprocal weights.

Rank reciprocal weights, using the same notation as before, may calculated as

$$W_i = \frac{1/R_i}{\sum_{i=1}^{N}(1/R_i)} \times 100\% \qquad (4.3)$$

When comparing the methods in Table 4.3, note that the rank reciprocal method gives the highest weight for the first-ranked attribute. One might choose among the weighing methods according to which provides the closest approximation to the independently judged weight for the highest ranked attribute.

Table 4.3 Calculation of Weights by several formulas

Method		Formula	Attributes (ref. Table 4.2) A	B	C	E	D	Total
Uniform		$W_i = 100\% / N$	20	20	20	20	20	100
Rank Sum	(A)	R_i^a	1	2	3	4	5	
	(B)	$N - R_i + 1$	5	4	3	2	1	15
	(C)	$W_i = \frac{(B) \times 100\%}{\Sigma(B)}$	33	27	20	13	7	100
Rank Reciprocal	(D)	$1 / R_i$	1	.5	.33	.25	.20	2.28
	(E)	$W_i = \frac{(D) \times 100\%}{\Sigma(D)}$	44	22	14	11	9	100

4.3.3.2 Weighted evaluation of alternatives

Once weights have been assigned to attributes, the next step is to assign numerical values regarding the degree to which each alternative satisfies each attribute. This is generally a difficult judgment task using an arbitrary scale of; say, 0 to 10 inclusive to reflect relative evaluations for each alternative and each attribute.

Example: Suppose that we are comparing two alternatives on the basis of how well they satisfy the five attributes having rank reciprocal weights developed in Table 4.5. The attributes, together with the subjective evaluation of how well a particular alternative meets each on the basis of a scale of 0 to 10, are shown in Table 4.4.

Table 4.4 Evaluation Rating Example

Attribute	Alternative (ref. Table 4.2)			
	A-1	A-2	A-3	A-4
Machine Performance	7.5	9	7.5	4
Cost	6	7	8	5
Serviceability	10	7.5	7.5	4
Riskness, lack of	8	6	4	6
Management/engineering effects	8	6	4	6

Table 4.5 Weighted evaluation of alternatives

		Attributes (ref. Table 4.2)					
		A	B	C	E	D	Total
Normalized Attribute Weight		44	22	14	11	9	
Alternative A-1	Evaluation rating	6	7.5	10	8	8	
	Weighted evaluation	26.4	16.5	14.0	8.8	7.2	72.9
Alternative A-2	Evaluation rating	7	9	7.5	6	6	
	Weighted evaluation	30.8	19.8	10.5	6.6	5.4	73.1
Alternative A-3	Evaluation rating	7.5	8	7.5	4	4	
	Weighted evaluation	32.8	17.5	10.9	4.4	3.5	69.2
Alternative A-4	Evaluation rating	4	5	5	6	6	
	Weighted evaluation	17.5	10.9	5.8	6.6	5.3	46.1

Once the evaluations have been made, the results can be calculated as in Table 4.5 to arrive at weighted evaluations of attributes for each alternative. Thus the summed weighted evaluation is 72.9 for alternative A-1 and 73.1 for alternative A-2, as calculated using the following equation:

$$\text{Weighted evaluation} = (\text{normalized attribute weight} \times \text{evaluation rating}) \div 10 \qquad (4.4)$$

This indicates alternative A-2 is marginally better even though it happened to have lower evaluation ratings for three out of five attributes, A-3 and A-4 is obvious lower than other two.

4.4 Evaluation of underwater control system

4.4.1 Evaluation criteria of underwater control system

Evaluation of a system starting from criteria selection, in the following sections we will try to summarize some of the important criteria of underwater control system evaluation. Since underwater control system covers a wide range of varieties, it is not possible to find out evaluation criteria for all the system, however, there are some common evaluation criteria for such systems. That is our goal to define those criteria.

4.4.1.1 Functional evaluation

Functional evaluation has to cover all the "must" and most of the "nice to have" type of customer requirement. Since all the different type of system has their own special requirements, so a complete list functional requirement is not possible to be made. Many of systems we discussed in Chapter 1 and 2, are intervention tool type, and that is also the interest of us.

In the follow sections, we are going to define some of those "Must" and "May" based on basic requirements for underwater intervention control system.

For example, typical "Must" requirements for the Intervention Control System normally look like,

The intervention control system must:

be designed for control of

- Handling equipment on deck.
- Functions during the intervention task

be designed for monitoring of

- Handling equipment on deck.
- Status during running.
- Functions during the intervention task
  - It should be confirmed that Reliability and suitability of the subsystems within an ROV spread

The typical "May" requirements normally look like,

- The control console shall have an operator friendly design.
- The control room shall have proper lighting, ventilation and heating

To be able to evaluate a problem, we need to apply the techniques introduced in previous sections to find out the criteria can be used. The examples listed above are just typical customer requirements. They have to be translated into useable criteria before put them into evaluation form.

4.4.1.2 Performance evaluation

Most of performance criteria are closely connectedly the specific product which we have covered general performance requirement in earlier section. Later in Chapter 5, we will use Tie-in equipment to illustrate the evaluation of some performance criteria related to that equipment.

4.4.2 Reliability concern of system

In order to design a reliable equipment, the designer should also adopt the idea of Reliability Engineering. The reliability engineering is that by using a standard set of mathematical of statistical methods and analyses to predict the reliability of an item, and to identify where reliability of an item can be improved by design changes.

4.4.2.1 Hardware Reliability

Criteria in the area of reliability should address the significant issues that relate to attainment of specification reliability goals. The goals are normally expressed terms of the length of time that the system will operate without experiencing a failure or the planned life expectancy. Reliability design criteria should always be stated in quantitative terms that can be easily related to the total or a specific portion of the design. The detailed calculation and theories about reliability analysis are well presented in a number of literatures, so the following is just a brief review some definitions and formula related to reliability analysis.

The following are definitions and formula related to reliability calculation,

- Reliability
  The probability that an item of equipment will perform its intended mission without failing assuming that the item is used within the condition for which it was designed.
- Failure.
  An item is considered to have failed when it cannot perform to the requirements for which it was designed.
- Failure Rate.
  A numeric value that predicts the number of failure rates are assembly, or piece part that will occur during one hour of operation. Failure rates are developed using tests, field experience, and other significant data. Dividing the number of failures that occurred over a specific length of time by the length of time results in the failure rate.

$$\lambda \text{ (Failure Rate)} = \text{Number of Failures} / \text{Total operating time} \quad (4.5)$$

- Mean Time Between Failure (MTBF)
  The reciprocal of a failure rate that predicts the average number of hours that an item, assembly, or piece part will operate before it fails.

$$MTBF = 1/\lambda \quad (4.6)$$

- Mission Reliability
  One of the prediction that is used to gauge how an item might perform is its predicted mission reliability. This is expressed as the probability of successfully completing a mission of a specified length.

$$R(x) = e^{-\lambda t} \quad (4.7)$$

Where:
R(x) = Probability of success
e = natural logarithm base
λ = failure rate
t = mission duration

4.4.2.2 Testability

The criteria for testability are interrelated with the criteria for maintainability. Testability criteria are concerned with the ease of locating and isolating portions of the system that experience a failure. Test of system can be performed at any stage of system operation. The ease and accuracy of testing achieved in a system design have direct impact on meeting maintainability goals. Testability must be designed into a system rather than be an after thought. Definitions related to testability are as follows:

- Testability.
  A design characteristic that allows the status (operable, inoperable, or degraded) of an item to be determined and the isolation of faults, with the items to be performed in a timely manner.
- Built-In Test
  An integral capability of the mission system or equipment which provides an automated test capability to detect, diagnose, or isolate failures.
- Built-In Test Equipment
  Hardware which is identifiable as performing the built-in test function; a subset of Built-In Test .
- Fault Isolation Time.
  The elapsed time between the detection and isolation of a fault.
- Fault Detection Rate.
  The ratio of failure detected by Built-In Test or other testing procedures to the failure population.
- Fault Resolution.
  The degree to which a test program or procedure can isolate a fault within an item; generally expressed as the percentage of the cases for which the isolation procedure results in a given ambiguity group size.
- Off-Line Testing.
  The testing of an item with the item removed from its normal operating environment.

4.4.2.3 Maintainability

Maintenance should be considered early in system design. Maintainability of surface and subsea equipment can be enhanced by:

- Designing equipment for accessibility and easy maintenance.
- Designing control system assemblies to be retrieved independently from subsea completion hardware.

Maintainability criteria are directed toward the inherent ability of the designed equipment to be maintained. These criteria address concepts that should be included in the design that aid in the performance of maintenance tasks. Physical design attributes can be listed in tabular form as a guide for design engineers. The goal of maintainability is to be able to accomplish a repair within a predetermined time limit.

Definitions about Maintainability:

- Maintainability.
  The probability that a failed item can be repaired in a specified amount of time using a specified set of resources is called maintainability.
- Mean Time to Repair (MTTR).
  The average time required to perform maintenance over a specified operating period is the Mean Time to Repair (MTTR).

$$MTTR = \overline{T}_p + \overline{T}_{FI} + \overline{T}_A + \overline{T}_{CO} + \overline{T}_{ST} = \sum_{M=1}^{m} \overline{T}_M \quad (4.8)$$

Where: $\overline{T}_P$ = Average preparation time

$\overline{T}_{FI}$ = Average fault isolation time

$\overline{T}_{FC} = \overline{T}_D + \overline{T}_I + \overline{T}_R$

$\overline{T}_D$ = Average disassembly time

$\overline{T}_I$ = Average interchange time

$\overline{T}_R$ = Average reassemble time

$\overline{T}_A$ = Average alignment time

$\overline{T}_{CO}$ = Average checkout time

$\overline{T}_{ST}$ = Average startup time

$\overline{T}_M$ = Average time of the M^{th} element of MTTR

- Mean Man-Hours per Maintenance Action (MMH/MA).
  The average time required to perform a maintenance action. The MMH/MA is used to develop a prediction of the total quantity of labor that will be required to perform maintenance.

- Mean Man-Hours per Operating Hour (MMH/OH).
  The ratio of man-hours required to perform maintenance to one hour of mission.

$$MMH / OH = \frac{(MTTR \times C \times F)}{MTBF} \quad (4.9)$$

Where: MTTR = Mean time to repair
C = Crew size
F = Operation service ratio
MTBF = Mean time between failures

- Fault Isolation.
  The act of identifying a failure to the level that will enable corrective maintenance to begin.

- Maintenance Task.
  Any action that is taken to fix a failed item or prolong the serviceability of an item.

4.4.3 The Human reliability

As we have discussed in Chapter 3, all the underwater systems are either manual or supervisory controlled, the human operator is one of the most important element in the whole system. Beside rebust design of system hardware and program, the performance of the human operator is also very important at the time of executing instruction.

To obtain a highly reliable system, the reliability analysis should not just limited to hardware, software reliability, but also the operator's reliability. In order to find out how reliable a system really is, it is important to get some idea about the behavior of a human operator to be placed in a complex system. Much of research work has been done to find out the cognitive and reaction pattern, response time and error probability of human operator. The following section is a brief introduction about human reliability.

4.4.3.1 Human Errors

Every human-machine system contains certain functions that must be performed by a human operator. Even the so-called fully automated systems need human interventions in monitoring and maintaining. If the variability in human performance is recognized as inevitable, then it is easy to understand that when humans are involved, errors will be made, regardless of the level of training, experience, or skill.

As the human-machine systems required to be more reliable, human influence becomes more and more important for the whole control system. The effort that is sometimes spent in designing ultra-reliable equipment is often negated by human error.

Human errors are said to occur when the performance is outside the predefined tolerance limits. Typically, the errors realize as a failure to perform a required action, or its performance in an incorrect manner, out of sequence, or at an incorrect time (Park, 92).

1. Definition of Human Error

Human error can be formally defined as "a failure on the part of the human to perform a prescribed act (or the performance of a prohibited act) within specified limits of accuracy, sequence, or time, which could result in manage to equipment and property or disruption of scheduled operations" (Park, 92). It is an out-of-tolerance action, or deviation from the norm, where the limits of acceptable performance are defined by the system.

The major cause of human error is inherent human variability. A human being is variable by nature; no one does anything the same way twice. Sheer variability results in random fluctuations of performance that are sometimes great enough to produce error, which can only be controlled by acquiring skill through training,

2. The Nature of Human Error

Although, there are certain similarities between human (with multiple organs and functions) and machine (with multiple components and functions) in terms of their proneness to failure, which lead to the parallelism of the methods of analysis in each, the human failure process has its peculiarities, too.

Probably, the most important difference is that the human errors are of randomly recurring type, whereas hardware failure condition is irreversible by itself. Human errors that do not result in system failure are often reversible. Hardware reliability is typically concerned with the irreversible failure.

A second difference is that a human continually improves his or her performance from learning unlike the machine counterpart. Learning and adoption during performance will be significant features of many situations.

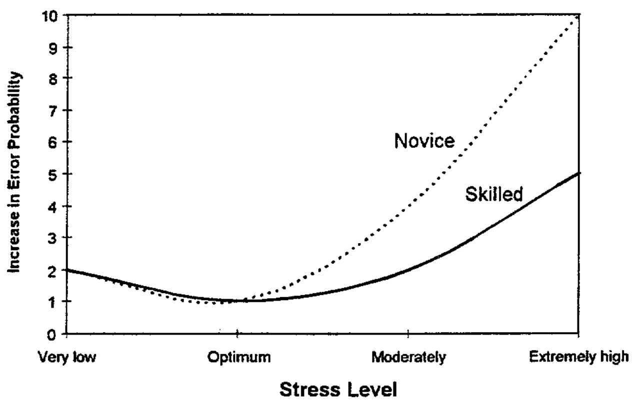


Figure 4.4 Effects of Stress and Experience on Human Error Probability in performing routine tasks (Data from Miller and Swain, 86)

Study from Mill and Swain shows that the human performance and stress follows a nonlinear relationship (Figure 4.4): When the stress is moderate, the performance level is highest. Also, the human performance may not be independent of the past performance record (autocorrelation), especially when the human has any preset low performance goal. Therefore, the parameters of the human variables should be obtained under conditions close to operational reality, considering the actual physical, emotional, intellectual, and attitudinal characteristics of the person to operate the machine (Park, 92).

1) Why people err

Since many of human error results from inadequacies in system design, in order to build a reliable human-machine system, design factors that induce human errors should be scrutinized and eliminated methodically.

(1) Task Complexity

Tasks differ in the amount of mental processing required. However, humans generally have similar performance limitations and process information similarly. These universal capacity limitations cause people to make more errors in more complex tasks.

Capacity limitations in short-term memory and recall problems in long-term memory strongly affect human performance reliability. Complex task sequences in a specific order overstrain human memory. Written procedures and detailed checklists can be used to unburden the operators of memorizing all the task elements and their correct sequential order.

(2) Error Likely Situations

Error likely situations are identified as work situations where the human engineering (HE) is so poor that errors are likely to occur. These situations overtax operators in a manner that is not compatible with their capabilities, limitations, experience, and expectations. For instance, any design that violates a strong population stereotype could be considered error likely.

This work situation approach is rooted in the Human Engineering design philosophy that the system should be fitted to the operator, not vice versa. The work situation approach emphasizes the identification of error-inducing conditions and their remediation. This approach assumes that errors are more likely to occur for reasons other than operator's faults. Thus, accident proneness applies to work situations, not people.

Situational task and equipment characteristics that predispose operators to increased errors include the following:

Inadequate work space
Poor layout design
Poor environmental conditions.
Inadequate training and job aids procedures.
Poor supervision.

4.4.3.2 Human Behavior in a Human-Machine System

In any human-machine systems, human activities are required for monitoring, adjusting, maintenance, and other normal operations as well as for coping with unusual disturbances that place a system at risk. In general, each human, individually or as a member of a team, must perceive information (from displays, environmental conditions, or procedural instructions) about the state of the system or subsystem for which one is responsible. The human operator must then process that information to determine what action or inaction should be taken, and then take it.

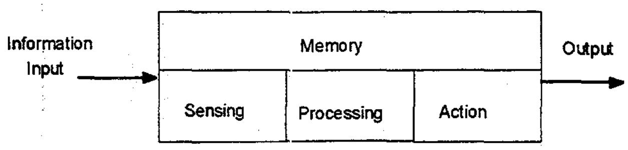


Figure 4.5 Human Component in a Human-Machine System

In this chain of events, humans essentially serve the three basic functions with the support of the fourth function: human memory. They are depicted schematically in Figure 4.5.

Human error occurs when any element in this chain of events is broken due to:

1. Input errors: errors of sensory or perceptual input.
2. Mediation errors; errors of mediation or information processing.
3. Output errors: errors in making physical responses.

Many of human error results from inadequacies in system design that create favorable conditions for error occurrence. Space does not allow the detailed review of all human factors theories. However, understanding the basic human capabilities is essential in creating a reliable environment that allows for inherent human psychomotor limitations.

1. Synthesis of Machine Reliability and Human Reliability

Human performance concerns both time discrete and time continuous tasks. Human reliability is expressed in terms of demand reliability for the first and of time reliability for the second. By combining the reliability appropriately with machine reliability, a total human-machine system reliability figure for the human performance in some specific task or job can be calculated.

2. Analytic human Reliability

Human error probabilities or human reliability are useful, not only in estimating human-machine system reliability, but also in other human engineering activities such as allocating functions between human and machine (based on reliability with and without the human), quantifying the error likelihood and consequences of human engineered equipment, and estimating the success of personnel training programs.

1) Measurement of Human Error

Human performance concerns both time discrete and time continuous tasks. Data on reliability are expressed in terms of failures per event for the first and failures per unit time for the second.

2) Human Error Probability in Discrete Tasks

A task is discrete if its content is well predefined with a definite beginning and ending (not unfolding in time).

The basic unit of human reliability in discrete tasks is the Human Error Probability (HEP). It is the probability of an error occurring during a specified task. The time allotted is either implicit or unspecified.

HEP is estimated from the ratio of errors committed to the total number of opportunities for that error:

$$HEP \cong \hat{p} = \frac{\text{number of human errors}}{\text{total number of opportunities for the error}} \tag{4.10}$$

The successful performance probability of a task (or tusk reliability) can be generally expressed as HEP. This is essentially equivalent to the measure of achieved equipment reliability. Thus. when we speak of the reliability of performance of an elemental human task, we are speaking of the probability of successful performance per demand

Table 4.6 presents general HEP estimates derived from various existing data sources and modified by the independent judgments of two human reliability analysts. Some of the estimates are based directly on data collected on tasks. In other cases the tasks were broken down into smaller bits of behavior that could readily be combined with existing data or with the experience of the analysts. Then, the estimates of HEPs for the individual behavioral units were combined into estimates of HEPs for larger units of behavior.

Table 4.6 General Operator HEP Estimates (Park, 92)

Estimated HEPs	Activity
.0001	Selection of a key-operated switch rather than a nonkey switch (this value does not include the error of decision where the operator misinterprets the situation and believes the key switch is the correct choice).
.001	Selection of a switch (or pair of switches) dissimilar in shape or location to the desired switch (or pair of switches), assuming no decision error; for example, the operator actuates the large handled switch rather than the small switch.
.003	General human error of commission, e.g,, misreading the label and therefore selecting the wrong switch.
.01	General human error of omission when there is no display in the control room of the status of the item omitted, i.e., failure to return the manually operated test valve to the proper configuration alter maintenance.
.003	Errors of omission, where the items being omitted are embedded in a procedure rather than at the end as above.
.03	Simple arithmetic errors with self-checking but without repeating the calculation by redoing it on another piece of paper.
1/x	Given that an operator is reaching for an incorrect switch (or pair of switches), he or she selects a particular similar-appearing switch (or pair of switches), where x is the number of incorrect switches (or pairs of switches) adjacent to the desired switch- (or pair of switches); the l/x applies up to five or six items; beyond that point the HEP would be lower because the operator would take more time to search; with up to five or six items' the operator does not expect to be wrong and therefore is more likely to be less deliberate in searching
.1	Given that an operator is reaching for the wrong motor operated valve (MOV) switch (or pair of switches), he or she fails to note from the indicator lamps that the MOV is already in the desired state and merely changes the status of the MOV without recognizing that he or she had selected the wrong switch (or pair of switches).
~ 1.0	Same as above, except that the state of the incorrect switch (or pair of switches) is not the desired state.
~ 1.0	If an operator fails to operate correctly one of two closely coupled valves or switches in a procedural step, she or he also falls to correctly operate the other valve.
.1	The monitor or inspector fails to recognize the initial error by the operator; with continuing feedback of the error on the annunciation panel, this high HEP would not apply.
.1	Personnel on different work shifts lid' to check the condition of the hardware unless required by a checklist or a written directive.
.5	Monitor fails to detect undesired position of valves, etc., during

Estimated HEPs	Activity
	general walk around inspections, assuming that no checklist is used.
.2 ~ .3	General HEP given very high stress levels where dangerous activities are occurring rapidly. Given severe time stress, as in trying to compensate for an error made in an emergency situation, the initial HEP, y, for an activity doubles for each attempt, *n*, after a previous incorrect attempt, until the limiting condition of an HEP of 1.0 is reached or until time runs out; this limiting condition corresponds to an individual becoming completely disorganized or ineffective.
~ 1.0	The operator fails to act correctly in the first 60 Sec after the onset of an extremely high stress condition, e.g., a large lot of coolant accident (LOCA).
.9	The operator fails to act correctly after the first 5 win alter the onset of an extremely high stress condition.
.1	The operator fails to act correctly alter the first 30 win in an extreme stress condition.
.01	The operator fails to act correctly alter the first several hours in a high stress condition.
y	Seven days alter a large LOCA, there is a complete recovery to the normal HEP, y, for any task.

The basic HEPs are to be modified by assigning higher value to unfavorable situations to reflect such factors as psychological stress, quality of HEP of controls and displays, quality of training and practice, presence and quality of written instructions and method of use, dependence of human actions, type of display feedback, and personnel redundancy.

An aid to applying such data to similar operational situations at hand is the well-known phenomenon of behavior constancy. Human behavior is constant in many tasks on different machines, that is, there is behavior similarity despite equipment dissimilarity.

3) Human Error Rate in Continuous Tasks

Tasks such as vigilance (scope monitoring), stabilizing, tracking (automobile operating), and so forth are known as time continuous tasks in which the task content unfolds continuously in time. The reliability modeling of such tasks is analogous to the classical time continuous reliability modeling.

Since the human errors are of randomly recurring type (with increasing error counts), general error processes are very difficult to model mathematically. However, when the error process is independent of the past history (with independent increments), the process becomes Poisson type.

By analogy to the arrival rate (or intensity function), define the human error rate $\lambda(t)$ as

$$\lambda(t)dt = \text{Prob}\{\text{at least an error in } [t, t+dt)\} = E[\text{number of errors in } [t, t+dt)] \quad (4.11)$$

in a narrow interval dt near t.

Human error rate is estimated by divining the errors committed by the total task duration:

$$\lambda \cong \hat{p} = \frac{\text{number of errors}}{\text{total task duration}} \quad (4.12)$$

4) Human Reliability

Reliability is the antithesis of error likelihood. Human reliability is then defined as the probability that performance will be error free for a specified duration.

The basic unit of human reliability is the HEP or error rate defined in the previous section. By combining these measures in assorted ways, the analyst can calculate a total reliability figure for human performance in some specific task or job.

5) Human Reliability in Repetitive Discrete Tasks

In a series of repetitive trials of a given task, a human can fall to perform a prescribed act (or perform a prohibited act), thus causing a human error In this context it is sometimes of interest to know a human's reliability of completing a prescribed sequence of successive trials.

Assume that the error probabilities are stationary and independent of the past performance under some favorable conditions. Given the HEP per trial, p (estimated by p), the human (interval) reliability that a prescribed sequence of successive trials from n_1 through n_2 are completed without any error is

$$R(n_1, n_2) = (1-p)^{n_2 - n_1 + 1} \quad (4.13)$$

When the HEPs are time varying as specified by pi, possibly due to fatigue or learning, the process is nonstationary. Park discusses a mathematical model describing human reliability with learning as a nonstationary Bernoulli process.

If the HEPs are dependent on the past performance, the error process is non-Markovian. No general theory on "non-Markov chain" exists yet. The total reliability figure may still be obtained by multiplying the terms involving the conditional HEPs associated with the trials, but it may be difficult to obtain the data for dependent HEPs as well as to manipulate them.

6) Human Reliability in Time Continuous Tasks

In the context of a time continuous task it is sometimes of interest to know the reliability of performing the given task successfully during a specified interval. Here, the human error condition is treated as an event without any duration.

Assume that the error rates are stationary and independent of the past performance (Poisson error process) under some favorable conditions. Given the error rate, A(estimated by A), the human (interval) reliability that a given task of specified duration *[t,. 4]* is performed successfully without any error is

$$R(t_1,t_2) = \exp[-\lambda(t_2-t_1)] \tag{4.14}$$

When the error rate is time varying as specified by A (t), possibly due to vigilance effect, fatigue, or learning, the process is nonstationary. Park generalizes Eq. (4.14) as

$$R(t_1,t_2) = \exp[-\int_{t_1}^{t_2} \lambda(t)dt] \tag{4.15}$$

and discusses a mathematical model describing human reliability with learning as a non-homogeneous Poisson process.

The error process can be completely general and dependent on the past performance, with nonexponential interarrival distributions. Except in a few special cases, such processes are not generally tractable.

7) Personnel Redundancy

Most studies of human reliability have been limited to the behavior of individuals operating independently. However, where personnel backup is anticipated for some of the tasks, it is necessary to account for the redundancy effect of additional surveillance on the increase in task reliability that would accrue. For example, to minimize the possibility of human error in carrying out any procedure involving a nuclear device, the Department of Defense has developed the "two-man concept".

If the human performance reliability of one operator is R_1, the two-man team reliability, R_2, is

$$R_2 = 1-(1-R_1)^2 \tag{4.16}$$

In estimating human reliability, however, a slight modification of the hardware redundancy assumption may be necessary. Unlike the devoted backup machine, a second individual may not always be available or attentive to back up the first individual. Therefore, when two men are working together to perform a task, their team reliability may be somewhat less than the ideal value derivable from Equ.(4.16) . In this case a weighted average of R_1 and R_2 may be used to consider part-time personnel redundancy.

4.4.4 Ergonomic analysis

4.4.4.1 Evaluation guideline for ergonomic requirement of system

Ergonomics is the science of fitting the environment and activities to the capabilities, dimensions, and needs of people. Ergonomic knowledge and principles are applied to adapt working conditions to the physical, psychological, and social nature of the person. The goal of ergonomics is to improve performance while at the same time enhancing comfort, health, and safety. In particular, human-machine interaction efficiency, comfort, health, and safety problems can be solved by applying ergonomic principles.

Ergonomic analysis is a very important part of the control system we are dealing with, since all the control activities are close related to human operator, so the layout of the control panel, arrangement of the control room, light, noise and ventilation etc. are very important to guarantee a good performance of operator.

The main purpose for ergonomics evaluation is to verify if the system designed has put human operator perspective into design, we have discussed some of the relevant consideration in previous chapter. The system should be designed on basis of the understanding of the way human operator decision making and thus give the maximum performance and lowest error probability, at same time the comfort and safety of the operator should also be considered. Modern control systems are more or less interacting with computer or display, the issues related to human-computer interaction will also be discussed. Kreifeldt (92) summarized factors related to system ergonomic design, we can see them in Table 4.7.

Underwater control system is a combination of “Machine”, “Work place”, “Computer” and “Information processing”. Therefore the evaluation criteria should be chosen for our system will be those factors related to decision making, anthropometry or safety, etc.. The evaluation can have the form such as check list or model simulation.

In the following sections, we are listed some of ergonomic related factors based on our guideline. We are going to develop some of those criteria in next chapter.

4.4.4.2 Evaluation criteria based on the relation with operator

The operationability of a control system is different with the functionality of the control system which is directly related to the movement of the actuator, but the operationability has very close relationship with the human being, the operator. Therefore, all the control actions must be designed with them in mind.

1. The human in the workspace

It is vital that a product “fit” it's intended user; in other words, it must be comfortable for a person to use. The geometric properties of humans-their height, reach, seating requirements, size of holes they can fit through, etc., are called anthropometric data (literally, “human-measures”). Much of this data has been collected by the armed forces because so many different people must operate military equipment on a day-to-day basis. Typical anthropometric data can be found in *HUMAN FACTORS DESIGN HANDBOOK* (Woodson, Tillman, 92). Since people come in a variety of shapes and sizes, it is important hat anthropometric data give a range of dimensions. The measures of humans are well represented as normal distributions. Typically, these measure are given for the fifty and ninety-fifty percentile. It is safe to assume that data for civilians does not differ significantly from that for military personnel.

Table 4.7 Ergonomic Design Problems (Woodson, *et. al*, 92)

Product/System	Examples	Issues
Tools	Consumer products (e.g., toothbrushes vacuum cleaners, cameras, hand tools)	Anthropometry Biomechanics Psycho-physics Aesthetics

Product/System	Examples	Issues
		Safety Preference Performance Satisfaction
Machines	Machines (e.g., industrial machines, artificial arms)	Anthropometry Biomechanics Decision making Response times Dynamic behavior
Workplace	Seating, furniture, lighting, cockpits	Safety Control display Information processing Anthropometry Physiology Biomechanics Safety Sensory system Productivity
Computers	Personal computers, calculators, video games, teaching pendants	Information Control display Decision making Errors Cognitive models
Information systems	Monitoring systems instructions/warnings signing systems data acquisition	Information Organization Perception Vigilance
People Systems	Service systems (operator teams, work cells)	Queuing Optimization Work/rest Group dynamics Organization

2. Product safety

Design for safety means ensuring will not cause injury or loss. There are two issues that must be considered in designing a safe product. First, who or what is to be protected from injury or loss during the operation of the product? Second, how is the protection actually implemented in the product?

There are three ways to institute product safety. The first way is to design safety directly into the product. This means that the device poses no inherent danger during normal operation or in case of failure. If inherent safety is impossible, as it is with most rotating machinery and vehicles, then the second way to design in safety is to add protective devices to the product. The third, and weakest, for of designing for safety is the use of a warning to point out dangers inherent in the use of a product. Typical warnings are by the use of labels, loud sounds, or flashing lights.

From safety evaluation point of view, because safety is such an important concern in military operations, the armed services have a standard-MIL-STD 882B, System Safety program Requirements- focused specifically on ensuring safety in military equipment and facilities. This document gives a simple method for dealing with any hazard, which is defined as a situation that, if not corrected, might result in death, injury, or illness to personnel or damage to, or loss of, equipment. MIL-STD 882B defines two measures of a hazard: the likelihood or frequency of its occurring and the consequence if it does occur. Five level of frequency of occurrence are given in Table 4.9 ranging from "improbable" to "Frequent." Table 4.8 lists four categories of the consequence of occurrence.

Table 4.8 The hazard consequence of occurrence (MIL-STD 882B)

Description	Category	Mishap definition
Catastrophic	I	Death or system loss
Critical	II	Severe injury, minor occupational illness, or major system damage
Marginal	III	Minor injury, minor occupational illness, or minor system damage
Negligible	IV	Less than minor injury, occupational illness, or system damage

Table 4.9 The Hazard Frequency of Occurrence (MIL-STD 882B)

Description	Level	Individual item	Inventory
Frequent	A	Likely to occur frequently	Continuously experience
Probable	B	Will occur several times in life of an item.	Will occur frequently
Occasional	C	Likely to occur sometime in life of an item.	Will occur serial times
Remote	D	Unlikely, but possible to occur in life of an item.	Unlikely, but can reasonably be expected to occur
Improbable	E	So unlikely, it can be assumed that occurrence may not be experienced.	Unlikely to occur, but possible

Table 4.10 The hazard-assessment matrix (MIL-STD 882B)

Hazard categories				
	I	II	III	IV
Frequency of occurrence	Catastrophic	Critical	Marginal	Negligible
A. Frequent	1	3	7	13
B. Probable	2	5	9	16
C. Occasional	4	6	11	18
D. Remote	8	10	14	19
E. Improbable	12	15	17	20

Table 4.11 Hazard-assessment result (MIL-STD 882B)

Hazard-risk index	**Criteria**
1-5	Unacceptable
6-9	Undesirable
10-17	Acceptable with review
18-20	Acceptable without review

3. Products Liability

Products liability is the name of the special branch of law dealing with alleged personal injury or property or environmental damage resulting from a defect in a product. It is important that design engineers know the extent of their responsibility in the design of a product. If, for example, a worker is injured while using a device, the designer(s) of the device and/or the manufacturer may be sued to compensate the worker and the employer for the losses incurred.

A products liability suit is a common legal action. Essentially, there are two sides in such a case, the plaintiff (the party alleging injury and suing to recover damages) and the defense (the party being sued).

Three different charges of negligence can be brought against designers in products liability cases:

1. The product was defectively designed. Typical charges include the failure to use "state-of-the-art" design considerations. Additional charges are that improper calculations were made, poor materials were used, insufficient testing was carried

out, and commonly accepted standards were not followed. In order to protect themselves from these charges, designers must:

- Keep good records to show all that was considered during the design process. These include records of calculations made, standards considered, results of tests, and all other information that demonstrates how the product evolved.
- Use commonly accepted standards when available. "Standards" are either voluntary or mandatory requirements for the product or the workplace; they often provide significant guidance during the design process.
- Use state-of-the-art evaluation techniques for proving the quality of the design before it goes into production.
- Follow a rational design process so that the reasoning behind design decisions can be defended.

2. The design did not include proper safety devices. As previously discussed, safety is either inherent in the product, is added to the product, or is provided through some form of warning to the user. The first alternative is definitely the best, the second sometimes a necessity, and the third the least advisable. A warning sign is not sufficient in most products liability cases, especially when it is evident that he design could have been made inherently safe or shielding could have been added to the product to make it safe. Thus, it is essential that the design engineers foresee all reasonable safety-compromising aspects of the product during the design process.
3. The designer did not foresee possible alternative uses of the product.
4. The product was defectively manufactured.
5. The product was improperly advertised.
6. Instructions for safe use of the product were not given.

4. Ergonomic Requirement for Control Console

In ergonomic point of view the different components of the work system (e.g., the environment, technology, work tasks, and the people) interact dynamically with each other and function as a total system. Since changing any one component of the system influences the other aspects of the system, the objective of ergonomics is to optimize the whole system rather than maximizing just one component. In an ergonomic approach, the person is the central focus, and the critical factors of the work system are designed to help the person be effective, motivated, and comfortable.

The consideration of physical, physiological, psychological, and social needs of the person is necessary to ensure the best possible workplace design for productive and healthy human-computer interaction. Table 4.12 shows ergonomic recommendations data for working environment and work station that improve the human interface characteristics.

Table 4.12 Ergonomic Recommendations for Work Environment and workstation (Smith, *et.al*, 92)

	Ergonomic Consideration	Recommendation
1.	Viewing screen	
	a. Character/screen contrast	7:1
	b. Screen character size	height =20-22 min of visual arc Width -70-80% of height
	c. Viewing distance	Usually 50 cm or less,
	d. Linear fresh rate	70 Hertz
	e. Eye viewing angle from horizon	10°-40°
2.	Illumination	
	a. No hardcopy	300 lux
	b. With normal hard copy	500 lux
	c. With poor hard copy	700 lux
	d. Environmental luminance contrast	1:3
	Near objects	1:10
	Far objects	40-60%
	e. Reflectance from surfaces	30%
	Working surface	80-90%
	Floor	40-60%
	Ceiling	
	Walls	
3.	HVAC (Heating, Ventilating and Air Conditioning)	
	a. Temperature-winter	20°-24°C (68°-75°F)
	b. Temperature-summer	23°-27°C (73°-81°F)
	c. Humidity	50-60%
	d. Airflow	0.15-0.25 m^3/sec
4.	Keyboard	
	a. Slope	0°-15°
	b. Key to area	200mm^2
	c. Key top horizontal width	12 mm (minimum)
	d. Horizontal key spacing	18-19 mm
	e. Vertical key spacing	18-20 mm
	f. Key force	0.25N - 1.5N (0.5-0.6N preferred)
5.	Workstation	
	a. Leg clearance	51 cm minimum
	b. Leg depth	(61 cm preferred minimum)
	c. Leg depth with leg extension	38 cm minimum
	d. Work surface height-nonadjustable	60 cm minimum
	e. Work surface height-adjustable for one surface	70 cm
	f. Work surface height-adjustable for two surfaces	70-80 cm Keyboard surface 59-71 cm Screen surface 70-80 cm
6.	Chair	
	a. Seat pan width	45 cm minimum
	b. Seat pan depth	38-43 cm minimum
	c. Seat front tilt	5° forward to 7° backward
	d. Seat back inclination	110°-130°
	e. Backrest height	45-51 cm

5 Developing a control system for tie-in equipment

5.1 Task Description

As we have discussed in chapter one, one of the major task for field development is the pipeline lay and connection.

The connecting task is to connect two ends pipes together or connect the pipe line to a structure. Different kinds of equipment have been used for such tasks, these are mainly two types of connection methods: mechanical connection and weld connection. The selection of tie-in methods is dependent of the pipeline construction (structure, diameter, wall thickness, stiffness, etc.) and whether it is a first-end or second-end tie-in. The following sections will give a brief review of different tie-in operation.

5.1.1 Pull-in operation procedure

Once the pipe line/umbilical is in place, the tie-in operation to the subsea facility can take place. The laying vessel has laid the pipe line/umbilical in a configuration on the seabed that allows for sufficient length for the tie-in operation. The first part of operation will be pull-in operation, afterwards the connection operation is taking place.

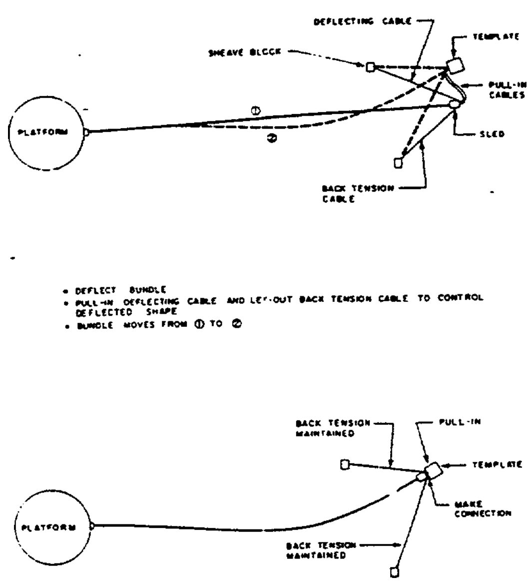


Figure 5.1 Tie-in of rigid steel pipe line using lateral deflection

5.1.1.1 *First-end tie-in of rigid steel pipe lines*

First end tie-in can be performed from a lay vessel. The tie-in is performed as a direct pull-in of the pipe line to the subsea facility. Pullwire from the surface through a pull-in tool is connected to the pipe line pullhead by ROV. The pipe line will be paid out from the laying vessel and carefully aligned in the front of the tie-in porch on the template/riser base laying on the seabed. During the last pull-in state guide pins or other suitable arrangements will control the final alignment of the outboard hub towards the inboard hub. After lock-in of the pullhead, pulls led the normal pipe lay away from the subsea installation. A connection tool can then make the connection between the hubs. Any expansion in the rigid steel pipe line during operation can be taken as an axial force from the pipe line to the inboard hub, or it can be absorbed in an inboard expansion loop on the template. When the pull-in equipment on the lay vessel is used, only the connection tool is required.

5.1.1.2 *Second-end tie-in of rigid steel pipe lines*

For a second-end tie-in of a rigid steel line, a direct pull is not generally possible. The pipe line is in contact with, and restrained by, the seabed (except for buoyant-tow installation methods), and the length of the pipe line has to be compatible with the distance to the tie-in facility. Therefore two basic methods are used for dealing with the length movement allowance and tolerances.

To simplify the tie-in of the pipe line to the subsea facility a flexible piece or tail may be put onto the end of the pipe line. This flexible jumper is then tied-in to the subsea structure in the same way as for flexible pipe line/umbilical.

Tie-in of flexible lines and flexible tails on steel lines have the same requirements to pull-in and alignment forces. They also have the same requirements to the pull-in and connection tools. The high flexibility of the lines enables it to be brought into a pull-in and lockdown assembly using relatively low forces. The forces are significantly lower than those needed to pull-in a rigid steel line. Due to low bending stiffness of the flexible line, the axial expansion force transferred to the structure is generally low. Expansion due to temperature and pressure during operation can be taken by the flexible line itself.

5.1.1.3 *Typical procedure for pull-in operation*

1. Establish guidance
2. Deploy tool and land it on to structure
3. Lock the tool onto structure
4. Establish pullwire connection
5. Pull of the pipe end
6. Lock termination of pipe onto structure
7. Retrieve tool to surface

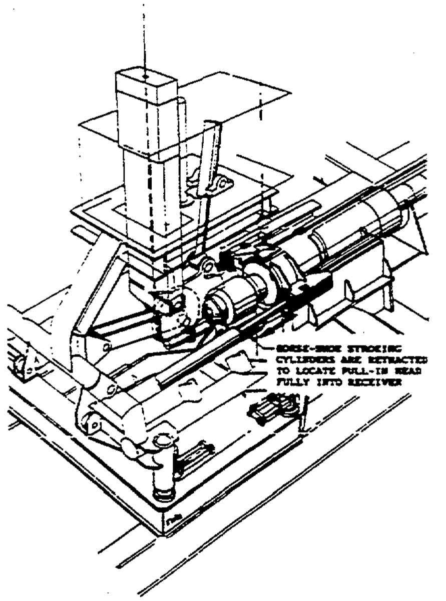


Figure 5.2 Pull-in operation

5.1.2 *Connection operation*

After the ends of pipe lines are pulled close to each other, the two ends will be connected. Connecting two ends of pipe line can occur at two situations, connection pipe line to he structure or replace damaged pipe line. Two of the procedures introduced has their advantages over one another on different cases.

5.1.2.1 *The procedure of hyperbaric welding connection*

One of the alternatives for connecting the two pipeline ends is to weld them together using TIG (Tungsten inert gas) hyperbaric welding. In the seventies a tie-in could last 3-4 weeks with manual welding, today this has come down to a 2-3 days operation using mechanized welding and highly trained personnel (Kristensen, 92).

The tie-in equipment and arrangement which uses welding differs a bit from the tie-in equipment uses mechanical clamp connector. The different equipment carries out the same tasks; tie-in and alignment of the pipe lines to be brought together.

Typical procedure for welding connection is as follows:

1. Initial alignment of pipeline

If the pipeline is not locked on any structure yet, an equipment is used to move the pipe such as the special H-frames can be used for initial alignment two ends of the pipeline.

The H-frame features horizontal (shifting) and vertical (lifting) movements. The H-frame trolley lifts the pipe into the right position, and the whole H-frame is "walking" on the seabed, moving the pipe over some distance if this is necessary (Figure 5.3).

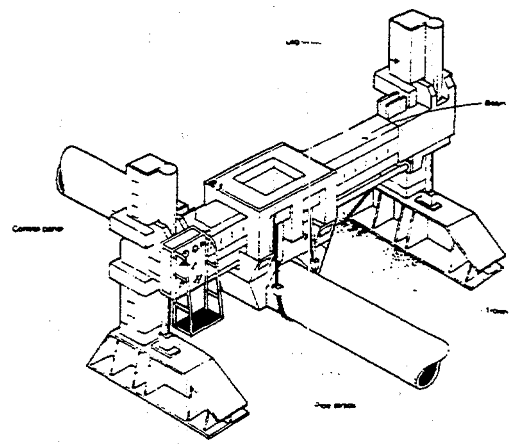


Figure 5.3 H-frame with pipe

2. Deploy and lower the welding habitat with alignment claws

When the two pipe ends are roughly brought into the right position, the welding habitat with alignment claws is deployed from the surface vessel and lowered down over the two pipe ends. When the habitat is just above the top of the pipelines, special alignment rams on the habitat is operated to line up the habitat with the pipelines.

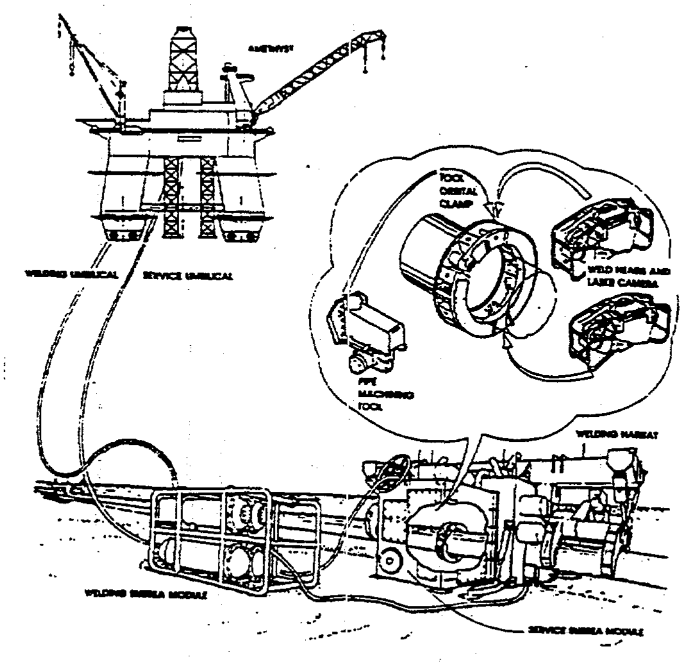


Figure 5.4 Automatic hyperbaric welding system

3. Lock down the habitat

After the habitat locked both ends of pipeline, the habitat is closed by using doors and seals, then water is forced out. The habitat has now a dry environment inside. A special service and power module is connected to the habitat.

4. Welding preparation

After the habitat is ready the welding preparations can start. A orbital clamp is placed around the pipe line end. If required, the ends will be cut, beveled and counterbored by a special pipe machining tool. A metrology report of the bevel is carried out. Then the ends are properly cleaned and dried to secure good weld properties and prevent corrosion of machined surfaces before welding starts.Fine alignment of the two ends

The tool orbital clamp does correction for ovality of the pipe line ends. When the alignment is acceptable the ends are ready for welding.

6. Lower and connect the welding subsea module to the welding habitat.

7. Install hyperbaric welding heads

Two hyperbaric welding heads are installed on the rotating face plate of the tool orbital clamp.

8. Pre-weld checks and prepare

9. Carry out welding, annealing of the weld if required

10. Visual inspection and non destructive testing of the weld

11. Corrosion protection is applied

So far, connection using TIG hyperbaric welding is complete.

New connection and repair of damaged pipeline are very suitable to use this method, however, this method can not be used for making multi-bore connection. To make connection of multi-bore pipe lines, the mechanical connection is a better alternative.

5.1.2.2 The working procedure of mechanical connection tool

Pullwire from the surface or the subsea installation through a tie-in tool is connected to the pipe line pullhead. A surface or subsea winch ties the two ends together. The subsequent relative alignment of the two pipeline ends to be connected is critical. The hubs must be brought into close alignment with each other before attempting the connection. Remote connection involves mechanical means of joining the pipeline to the pipe work in the subsea installation.

Table 5.1 Typical working procedure and associated control problem of mechanical connection

	Procedure/task	Control problem associated
1.	Attach/Detach guidance (guideline or mechanical)	ROV control
2.	Move connection tool to/from structure	ROV or deployment equipment control
3.	Lock the tool onto structure	Locking device - lock, release,

	Procedure/task	Control problem associated
	Release the tool from structure	backup
4.	Alignment of two termination hubs	Combined action of actuator and structure, position and angle
5.	Inspect and clean(if required) termination seal surface	Control of Brush, water-jet or similar for clean task, control of camera
6.	Brought termination hubs together	Linear actuation control - in, out, actuation force, end points
7.	Inserted seal ring between termination (if seal ring is not an integrate part of the clamp)	Normally integrated with clamp
8.	Place clamp over termination hubs	Linear actuation control - up, down, end position
9.	Force the hubs together towards seal ring by tightening the clamp	Angular/Rotation actuation - angle or force control
10	Clamp is tightened, the seal surface is pushed together	Built-in clamp construction
11	After necessary tightness is achieved, a pressure test is carried to verify the connection.	Pressure monitoring and registering

From that typical procedure for a connection operation, we can start to define required functions from the customer and task requirement.

5.2 Customer requirement

This section is trying to define the basic requirements of customer to the use of ROV spread interfaced with Tools for tie-in tasks. The goal will be to obtain standardized minimal requirement for tie-in system. This requirement is modified on basis of ISO 13628-9 Draft.

5.2.1 Functional requirements for Tie-in systems

The section also gives requirements to interfaces between the ROV and the Tool when a working ROV are used to physically guide or position a Tool into the landing site.

This section contains functional requirements to the elements within the various options of subsea tie-in systems.

1. General requirement

The primary objective for the tie-in system shall be to facilitate safe and cost efficient tie-in on subsea pipe lines.

The subsea tie-in system shall be designed as simple, reliable and robust as possible, to ensure safety of personnel and to prevent damage to the subsea tie-in system and/or the environment. No possible or realistic failure shall result in reduced safety for the involved personnel, or cause damage to involved equipment and/or environment.

2. Designed life time of the equipment

The subsea tie-in system must have a lifetime equal to that of the field (normally 10~30 years). Potential long-term effects on connectors and sealing surfaces must be taken into account when designing the tie-in system for reversibility.

3. Working and storage environment

- The tool will be stored indoor while it is not in use.
- The minimum design temperature for the subsea tie-in system is -20 °C.
- The maximal design temperature for the subsea tie-in system is +50 °C.
- Expected working depth < 1500 m.

4. Safety during operating the equipment and emergency

All tie-in operations shall be possible to interrupt in a safe manner and restart in the event of failure or adverse weather conditions. The tie-in task shall also be reversible at any stage in a safely manner.

- Cutting-loops shall be included for hydraulic functions with override possibilities to enable cutting of the loops with an ROV and hence prevent pressure lock in the respective hydraulic function.
- Back-up override systems shall be designed for subsea activation by use of ROV, without the need for additional surface support.
- Sensitive components or items that may be damaged during running, operation, ROV involvement or interactions with wires shall be protected.
- The tie-in system shall avoid snagging points for guidewires, lift wires and umbilicals
- Active hydraulic or electric components should not be left subsea.

5. Monitoring during operation

- Design of tool system should provide adequate access; maneuvering space and viewing position for working ROV and Observation ROV, to perform all inspection and manipulative work required during the installation and operation phase.
- All tool Functions shall have visual subsea status and position indicators visible from ROV, clearly indicating the respective Function status. Operations that pass through several discrete steps, shall clearly identify the various stages of the operations.

6. Deployment of the equipment

- The tie-in system shall be designed to be run through a moonpool and over the side, both from a rig and from a monohull vessel.
- The tie-in system shall be well balanced with the resulting center of gravity point straight below the handling cable attachment point.

7. Retrieval of the equipment

- All tool functions which upon failure may prevent retrieval of the tool system to surface shall have back-up override features. This shall include the release from both the permanently installed sub sea systems (where locking mechanism is used) as well as from the sea lines, modules or components.

- Pad eyes for emergency lifting shall be included on all Tool systems. Arrangement for purpose built subsea jacks should be considered for applications where direct pull from surface is unacceptable.

8. Other requirement

- For new subsea tie-in systems, where relevant experience foundation is limited, analyses shall be performed to document the operational feasibility.
- Tie-in tasks requiring special purpose designed tools and interfaces shall be carefully defined and planned in advance.
- The tool system shall be designed to facilitate easy maintenance, replacement of components and repair.
- Weight of the tool system, including the component module, shall be minimized for handling purposes.
- General operational support (observation, cleaning of seal areas, operation of valves etc.), should be performed by use of the ROV manipulators or dedicated tools without requirements for additional ROV modifications.

5.2.2 Control system requirements

5.2.2.1 General

This section contains general requirements to the Intervention Control System (ICS). The main components of the control system for a tie-in system are:

- Surface control system
- Surface/subsea communication unit
- Subsea control system

5.2.2.2 Functional requirement

1. General
   - The equipment shall be supplied complete with all necessary interface piping, instrumentation, cabling and hose jumpers so that no on-site installation is required except from connecting the units.
   - The tie-in system should be designed to cover complementary tasks in addition to the primary task.
   - The Intervention Control System (ICS) shall be optimized to reduce mobilizations/ demobilization time on the vessel.

2. Data archive and storage
   - The surface control system shall include facilities for computerized storage and printout of relevant feedback data from the various operations.

- The surface control system shall provide facilities for video recording of the tool system operations, including ROV operations for complementary work.

3. Monitoring

- The surface control container shall have min. Two off color monitors and provision for installation of two spare monitors. The total number of monitors shall reflect the maximum numbers of functions to be monitored simultaneously.
- Alarm shall be provided upon critical low pressure and reservoir levels in the hydraulic system.

4. Communication

- The surface control system shall provide facilities for monitoring applicable surface activities and for communication to crane/winch and ROV control cabins.
- The layout of the surface control container shall allow easy access to all components for maintenance and repair. Removable hinged side panels shall be included for protection and maintainability during onshore/offshore operations and transportation.
- The umbilical shall be fitted with a ground wire of necessary size to prevent electrical potential differences between the tool/ROV system and the surface equipment.
- A combined umbilical/lifting wire may alternatively be used. It shall be qualified by an acceptable test program to verify breaking strength and fatigue resistance.
- There shall be fluid compatibility between the tool system and the ROV.

5. Interface between tool and ROV

- Docking should allow for the ROV to perform complementary work and monitoring tasks throughout the operation.
- The umbilical design shall be suitable for the application required; particularly in respect to torque balance; tensile strength; elongation; fatigue bending and rough handling; combined with good flexibility and low weight to ensure easy handling and operation.
- Application of ROV surface control systems shall be based on standard, readily available ROV spreads.

6. Energy transfer capacity

- The size of electrical and hydraulic systems in ICS shall include 20% spare in the number of lines (functions).
- The umbilical shall contain necessary power cables, twisted pair signal cables and coaxial cables for video signal transmission. Minimum one spare electrical/signal cable each shall be included (fiber optic data transmission will be acceptable).
- In umbilicals containing hydraulic lines, the hydraulic return line shall always have a pressure higher than ambient to prevent sea water ingress.

- The hydraulic system shall be designed to maintain project specific cleanliness and water content requirements.

5.2.2.3 *Safety requirements*

- The tie-in system shall be designed with weak link connections between the lift wire and the tool system, and between the ROV and the tool system. Locations of the weak links shall be taken considering possibility and consequence for damages on the tool system or the subsea structure.
- The umbilical and/or lift wire attachments should include a feature for safe splitting of the umbilical and/or lift wire from the tool in case of vessel drifts off.
- Electrical equipment shall be water ingress protected with correct IP rating
- Subsea electrical units shall be installed in oil filled, pressure compensated compartments. The oil shall not be part of the hydraulic system.

5.2.2.4 *Environmental and space requirements*

- Space for surface equipment and personnel for operation of the equipment shall be made available.
- The surface control container shall enable deck positioning flexibility, e.g., location of doors; panels; cable inlets/outlets, etc.

5.2.2.5 *Ergonomic requirements*

- The control room shall have proper lighting, ventilation and heating.
- The control room shall be noise protected according to regulations.
- The control console shall have an operator friendly design. Control panels shall be easy readable with logical and understandable marking and multiplexer.
- The umbilical MQC plates shall be easy to operate. Guidance, alignment and orientation features shall be provided to ensure correct coupler alignment and prevent coupler damage during connection and disconnection.

5.2.2.6 *Other requirements*

- All control cables, piping, umbilical terminations, connectors, hoses and associated equipment shall be supported and protected adequately to prevent damage or contamination during testing, equipment handling and operation.
- The HPU installed shall be mounted on a sub-frame isolated from the lifting frame by elastomer mounts.
- The tool system shall have provision for flushing of the hydraulic system.

5.2.3 Typical functional requirement of guideline based mechanical tie-in equipment

Mechanical tie-in equipment has two main categories by the guidance during deployment- with Guideline and without Guideline. This section is a brief introduction of the procedure modified on basis of Kværner Energy's Pull-In and Connection Tool.

Table 5.2 Operation procedure and feedback requirements

Procedure and requirement	Original Feedback	Modified Feedback	Reason
1. Pre-dive operations			
1) Function test on the tool.			
2) Establish guidance.			
3) Pull-in wire to be reeled through the tool.			
4) Lifting wire to be connected to the tool.			
5) Connector to be loaded to the tool.			
2. Running of tool			
1) the tool to be ran into sea.			
2) the tool to be landed carefully.	ROV to observe	No change	
3) Tool fix itself to structure	ROV to confirm	Visual or Instrument confirmation required	Less space requirement and higher accuracy
4) Pull-test from surface to be performed to verify that the tool is locked.			
3. Pull-in wire establishment			
1) ROV to carry out pull-in wire. the tool to feed wire.			
2) ROV connect pull-in wire to pipe termination.			
4. Pull-in (second end):			
1) Pull-in to be performed by using pull-in winch until termination are located in front of pull-in funnel.			
2) Termination to be cleaned.			
3) Pull-in to be continued by the tool-mounted linear winch until termination head is connected to termination stroking mechanism.	ROV to verify	Visual or Instrument confirmation required	Less space requirement and higher accuracy
4) Final pull-in to be by termination stroke. Take up reel to apply constant tension.			
5) Pull head to be released and held.	ROV to verify	Visual or Instrument confirmation required	Less space requirement and higher accuracy
6) Termination Stroke to be retracted.			
7) Inspect/clean hub seal surfaces with inspection and cleaning tools.	ROV to inspect/clean hub	Visual inspection required	Less space requirement and higher accuracy
5. Connection operation:			
1) Connector to be moved in between hubs. Temporary protection cap to be knocked off.	ROV to verify	Visual or Instrument confirmation required	Less space requirement and higher accuracy
2) Termination stroke to be stroked so outboard hub is forced against seal plate and inboard hub.	ROV to verify	Visual or Instrument confirmation required	Less space requirement and higher accuracy
3) Engage Make-up Shuttle.			

Procedure and requirement	Original Feedback	Modified Feedback	Reason
4) Make-up torque unit to torque connector screw to achieve connect connection.			
5) Disengage Make-up Shuttle.			
6) Perform Connector Seal Test. Typical test pressure to be 30 bar. Holding period 10 minutes.			
7) Connector to be released.	ROV to verify	Visual or Instrument confirmation required	Less space requirement and higher accuracy
8) Lock the termination to the lower funnel.			
9) Funnel Lock to lock the lower funnel to the cradle and to release the lower part of the funnel from the tool.	ROV to verify	Visual or Instrument confirmation required	Less space requirement and higher accuracy
6. Tool retrieval			
1) Release the tool from structure.	ROV to verify	Visual or Instrument confirmation required	Less space requirement and higher accuracy
2) the tool to be retrieved to surface and stabilized.			
3) the tool to be landed and locked to the tool test and transport skid.			
4) Connector to be loaded into the tool.			
5) Pull-head should be lowered by connecting pull head to the dummy outboard hub. Dummy hub with pull head to be tilted down and pulled onto the skid.			
6) Wire insert to be loaded with new pin.			

5.2.4 Typical mechanical components of mechanical tie-in system

The basic components of a pull-in and connection system using mechanical clamp connector include the following main equipment:

- Pull-in tool
- Connection tool
- Clamp connectors including seals
- Pull-in wire
- Pull-in head
- Protection caps
- Hub assemblies
- Pull-in porches including funnels, guide posts, miniposts, etc.
- Alignment and orientation device.
- Control system
- Surface equipment
- Test and transportation equipment

5.3 Control system used for mechanical tie-in system

5.3.1 Required basic tool functions

From the nature of the task and custom requirement, the minimal number of function is determined the following requirement:

Table 5.3 Basic requirements for Mechanical Tie-in equipment

No.	Requirement	Associated control problem
1.	Able to keep tool at position	Confirmation of locking
2.	Able to transfer pull force to the structure	Tool structure
3.	Able to offer sufficient pull in a distance	Length of pull wire
4.	Able to apply sufficient pull in force	Power (Electrical or hydraulic)
5.	Able to remove protection on termination hubs	Actuation signal and feedback confirmation
6.	Able to inspection and clean contact surface	Visual image generating and transfer
7.	Able to lock termination on place	Actuation signal and feedback confirmation
8.	Able to release pull head from termination	Actuation signal and feedback confirmation
9.	Able to bring to termination towards each other	Actuation signal and feedback confirmation
10.	Able to hold connector on tool	Actuation signal and feedback confirmation
11.	Able to put the mechanical clamp on to the two termination hubs	Actuation signal and feedback confirmation
12.	Able to make tight contact between seal surface on two termination hubs	Actuation signal and feedback confirmation
13.	Able to carry out pressure test to verify the connection	Pressure and feedback pressure, result log and storage
14.	Able to release itself from structure (Normal operation)	Actuation signal and feedback confirmation
15.	Able to be retrieved to surface	Lift point
16.	Able to release itself and maintain the termination at safe status at accidental situation	Backup energy, sequential action
17.	Able to be helped from surface or ROV hotline to accomplish actions to release itself safely in accidental situation	ROV interface, cut line loop, stab-in connector

5.3.2 *Required basic control system function*

For a control system the functionality analysis will stand the following points:

Table 5.4 Requirements for control system

No.	Requirement	Possible solution
1.	It should be able to control all the possible circumstances may appear during operation	Case study
2.	It should guide and force the operator follow correct operation procedure, and avoid serious problem even a mistake was made.	Interlock check, critical function reminder, confirmation of action
3.	It should have ways of correcting previous made mistake	Cancel or resent function
4.	It should be able to override locked function	Manual override
5.	It should give indication of both system status and operation status	Message or indication light
6.	It should be able to present necessary alert message, help message, error message to operator	On screen message, indication light, alarm
7.	It should contain debug function and self detecting function	Built-in self detection routine
8.	It should have both audio and visual information presentation of the status	Loud speaker, screen, light, labeled button
9.	It should be able to communicate with other part of system	Intercom, Walkie-talkie, telephone
10.	It should be able to convey energy and control signal to different part of system	Cables, hoses, hardwire, hard pipe
11.	It should offer the operator a comfort working environment	Chair, table, air condition, interior light

5.3.3 *Required feedback information*

From chapter three, we learnt that the human operator has lost the senses to the status of equipment located underwater because of the long distance between work site and operator. Much of the information is the basis of a successful operation, no task can be completed if without them. Information needed for completing a task can be classified into two categories, operation status and system status information.

5.3.3.1 Operation status information

Many of feedback signals from the work site have to be transferred to the operator for monitoring the operation status during a tie-in operation. Some of the information can be used as an internal reference for other functions, and some of them are needed for operator decision making. Table 5.5 lists all the tool function can supply information related to operation status.

Table 5.5 Information related to operation status

Feedback from function	Information type	Acquisition method
Tool Lock Down	Position, End points	Visual verification Position sensor
Funnel Tilt	Position, End points	Position sensor
Termination Stroke	Position, End points	Position sensor
Connector Latch	Angular	Angular sensor
Funnel Hatch	Position, End points	Position sensor
Clamp Wedge	Position, End points	Position sensor
Clamp Bolts	Position, End points	Position sensor
Pull head Receiver	Position, End points	Position sensor
Wire Feeder	Angular	Angular sensor
Pull-In Winch	Tension/Force	Pressure transducer
Connector Elevator	Position, End points	Position sensor
Torque Tool Engage	Position, End points	Position sensor
Torque Tool Make	Cycle	Mechanical/digital counter
Center Box	Position, End points	Position sensor
Seal Test	Pressure	Pressure sensor

5.3.3.2 System Status information

System status can be represented by many of the system variables. Some of the variables are physical quantity such as pressure, flow, temperature and level. Others are control program internal status, such as function type, steps in process, etc.. The following table gives an overview of such variables needed to be presented to the operator.

Table 5.6 Information of system status

System variable	Information type	Acquisition method
Pressure of hydraulic system	Pressure	Pressure gauge/transducer
Reservoir level indication	Position	Position sensor
High temperature	Temperature	Temperature transducer
Gas/Fire	Gas/Smoke content	Gas/Smoke alarm
Filter status	Pressure	Pressure transducer
System Flow	Flow	Flow meter
Pump pressure	Pressure	Pressure gauge/transducer
Critical function indication	Flag	Program Flag
Function interlock indication	Flag	Program internal flag

5.3.4 Communication and media

Communication between surface and subsea control system can have many forms, RF (Radio Frequency); acoustic; directly link of electric or hydraulic signal. Comparison of these communication methods is listed below. Please note, the following comparisons are in general terms. The basic requirement is that the system selected can fulfill the task requirement. If one of the criteria is more important than other, or one of the operation condition is more favorable than other, the corresponding score will be higher.

There has no exist evaluation criterion for communication method for underwater application. The following criteria (Table 5.7) are made according to interview and survey of system designers. Calculations are based on Table 4.3. The resulted tables (Table 5.8, Table 5.9, Table 5.10, Table 5.11) are just indication of personal opinion of the people involved. Importance of each criterion to the overall system is arranged that the more important, the more front of the criteria is.

Table 5.7 Evaluation criteria of communication method

Criteria	Definition
Cost, Manufacture	Costs involved in manufacturing the communication equipment
Cost, Initial setup	Costs related to all the other equipment needed to utilize the specific method
Range, Operation	Working distance and water depth for specific method
Reliability, Operation	Reliability of operation the whole communication system
Space requirement	Space required for the communication equipment
Communication, Band width of channel	Speed and number of signal to be transferred
Faulty detection	Capability of detection faulty
Repair and replacement	Work related to repair and replacement of component to accomplish the task

Table 5.8 Evaluation of RF (Radio Frequency) communication system

Criteria	Scale (1 to 10)
Cost, Manufacture	9
Cost, Initial setup	9
Depth, Operation	2
Reliability, Operation	5
Space requirement	9
Communication, band width of channel	8
Range, Operation	10
Faulty detection	6
Repair and replacement	8
Total:	76.4

Table 5.9 Evaluation of Acoustic communication system

Criteria	Scale (1 to 10)
Cost, Manufacture	9
Cost, Initial setup	2
Depth, Operation	10
Reliability, Operation	6
Space requirement	8
Communication, band width of channel	7
Range, Operation	8
Faulty detection	6
Repair and replacement	2
Total:	69.7

Table 5.10 Evaluation of hydraulic umbilical system

Criteria	Scale (1 to 10)
Cost, Manufacture	6
Cost, Initial setup	10
Depth, Operation	5
Reliability, Operation	9
Space requirement	2
Communication, band width of channel	3
Range, Operation	5
Faulty detection	4
Repair and replacement	5
Total:	62.2

Table 5.11 Evaluation of Electric/Optic umbilical system

Criteria	Scale (1 to 10)
Cost, Manufacture	7
Cost, Initial setup	10
Depth, Operation	7
Reliability, Operation	10
Space requirement	8
Communication, band width of channel	10
Range, Operation	4
Faulty detection	10
Repair and replacement	8
Total:	80.6

Table 5.12 Summary of communication method evaluation

Communication method	Result	Comment
Radio Frequency	76.4	Long distance, small depth, low energy capacity, medium signal capacity, medium reliability
Acoustic	69.7	Long distance, large depth, low energy capacity, low/medium signal capacity, low reliability
Hydraulic umbilical	62.2	Medium depth, high energy capacity, low signal capacity, high reliability
Electric/Optic umbilical	80.6	Large depth, high energy and signal capacity and reliability

5.3.5 Subsea system

5.3.5.1 Valve pack

The control valve pack is the interface between control lines supplying hydraulic and/or electric power and signals from a surface/subsea control and power unit and the subsea tool to be controlled. The control valve pack contains valves that may be powered by hydraulic fluid, electric power, or both.

Subsea control system components should be protected from the environment and from the mechanical damage that can occur during transportation, handling and installation. An outer housing usually provides this protection. Other electrical components, such as pressure switches, pressure transducers, flowmeter, etc., are normally designed to operate at ambient subsea hydrostatic pressure.

For underwater control system, there following types of mechanical protection device can be chosen from:

1) To protect against mechanical damage by foreign object or during handling, the protection structure is formed with frame and open grid type of plate. It can only protect object that will cause mechanical damage for the control that might occur during operation. The cost for manufacturing is lowest, the same of level of protection.

2) Most of the control valves and transducers, such as solenoid valve, servo valve, digital valve pilot valve, etc., need to be separated from sea water. A sealed structure and a compensator act together to separate internal (dielectric fluid, not part of hydraulic system) and external fluid (sea water), and supply a small pressure difference (internal > external). This structure gives the system a much better protection against foreign objects and corrosion.

2. Instrument canister

When electronic device is used, such as onboard computer, PLC, modem, etc., it normally should be contained in a one atmosphere, dry air or nitrogen filled pressure vessel.

The protection canister has to take all the environment pressure, and seals all the possible leakage. The design of this canniest will require documented stress calculation and verification. This gives the system a maximum protection.

5.3.5.2 Subsea Hydraulic Power Unit (HPU)

The subsea HPU has to provide the same functionality as surface HPU, fluid storage, fluid conditioning (filtering), high pressure generation, and high pressure storage. A typical subsea HPU schematic is shown in Figure 5.5.

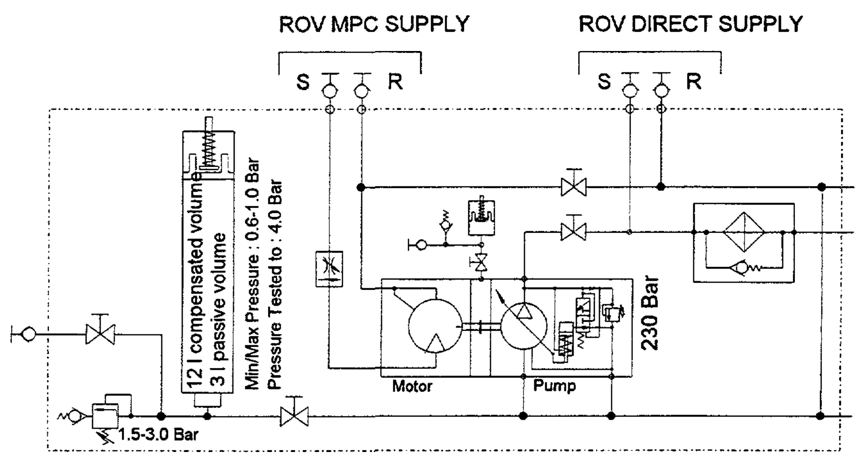


Figure 5.5 Typical Subsea Hydraulic Power Unit schematic

The HPU should be equipped with sufficient number and sizes of hydraulic pumps to satisfactorily keep up with minor internal leakage and normal system operation. The biggest difference with surface HPU is that the subsea HPU reservoir needs only to take up the differential volume in the hydraulic system operation.

5.3.5.3 ROV/Diver intervention.

In case of tie-in system mechanical or electronic/hydraulic system breakdown, the tool has to be retrieved to surface. External intervention is used to complete some functions to make sure the tool and system can be retrieved safely. In such cases, ROV or diver will be used to accomplish the work.

In most of the cases we are dealing with, since water depth is beyond human diver's safety reach, then ROV will be used. So sufficient access plus reaction/anchor points for

ROV should be provided in the location of potential work areas to ensure that divers or ROVs can do the required work.

All the control valves or stab-in positions for necessary functions are logically spread on the specially designed ROV/diver panel. Some of the functions also include cut line position to remove hydraulic block if everything else is failed.

5.3.6 *Typical control system operation sequence design*

During a typical tie-in operation by mechanical equipment such as PICT, a function chart representing the sequence of operation is necessary for clarify the operation logic flow. It could be used as a basis for control programming. Many of the functions and actions are actually subroutines.

Table 5.13 Functions required on control panel

Item	Description	Requirement
Off-line test	Test control system while the tool is not running	Test software and console hardware
Operation steps, non-critical function	Procedure of activating non-critical function	Relative simple, with interlock indication
Operation steps, critical function	Procedure of activating critical function	Force thinking, with possible to reverse, with interlock indication and emergency stop, not more than 5 steps
Online help	Instruction to operator about what to do next	Help the operator with no possibility of mis-interpretation the instruction. Can have form of text instruction, sequence lighting, etc.
Faulty detection/assistance	Procedure or program built-in for assist to locate faulty	Help the operator to locate the failure by presenting available sensor information or check list
Function override	Override functions which is not permitted in ordinary situation	Offer the possibility of force execute some critical function when needed.
Cancel function	Stop the current sequence	Stop previous inputted key sequence
Reset function	Reset all the system variable	Neutralize all the system variable as start status of system
Mode selection	Select between different operation mode	Switch between different operation mode, to make the operation easier and more fault proof.

1. Typical function chart for control system of mechanical tie-in equipment

From the basic requirements in Table 5.13, we can design a function chart for such a system to fulfill the requirements.

On a typical control console (Figure 5.6), two main mode switches, spring return switches and buttons are implemented. Some informations are presented in picture form. Meters and lamps are intergrated in the picture to give the operator a direct visual feedback about system status. Tool functions are controlled by individual buttons, the built-in lamps indicate the state of functions. Alarm and alarm reset button are also located on the same panel.

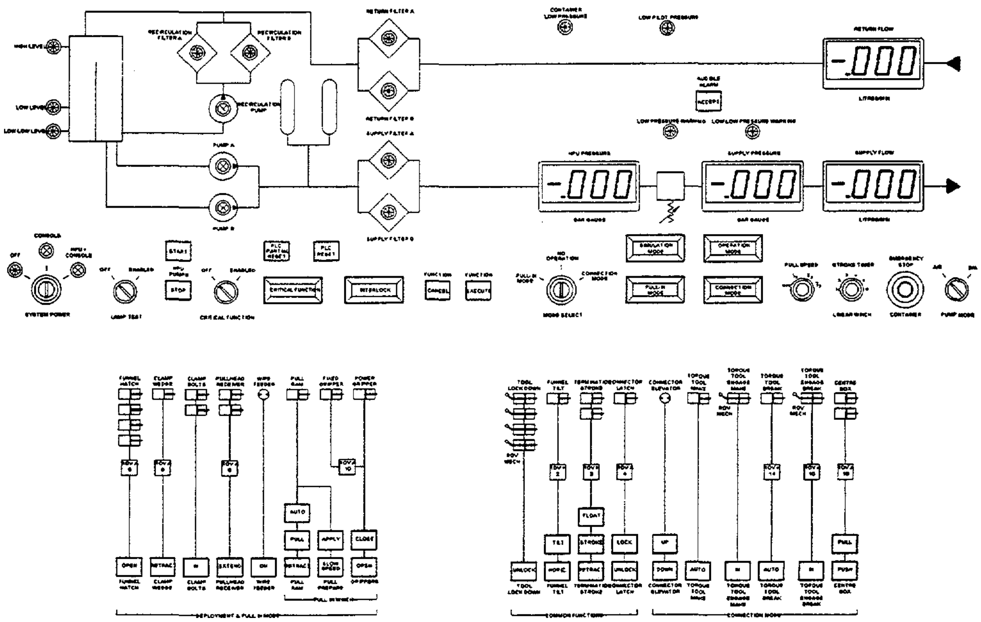


Figure 5.6 Typical arrangement of control console

Figure 5.7 illustrates the function chart of a control system for mechanical tie-in equipment. This system gives the possibility of operating functions individually. This system can also simulate the operation of all the functions when the system is off-line. Critical and interlock evaluation gives the system extra safety feature against human operating error.

The initial state of the control system is that external power is connected. When the mode switch System Power is switched to Console, the system is ready to start. In this state(Figure 5.8), all the system displays are on, and hardware test can be performed.

The system will return to initial state if System Power switch is set to Power Off and there is no operation at that time. If HPU pumps start button is selected, simulation sequence (Figure 5.9) can be started.

When the mode switch System Power is switched to HPU+Console and confirmed with function Enable, the system is ready to start in operation mode. If HPU pumps start button is selected, the operation sequence (Figure 5.10) will be started and the pumps are started.

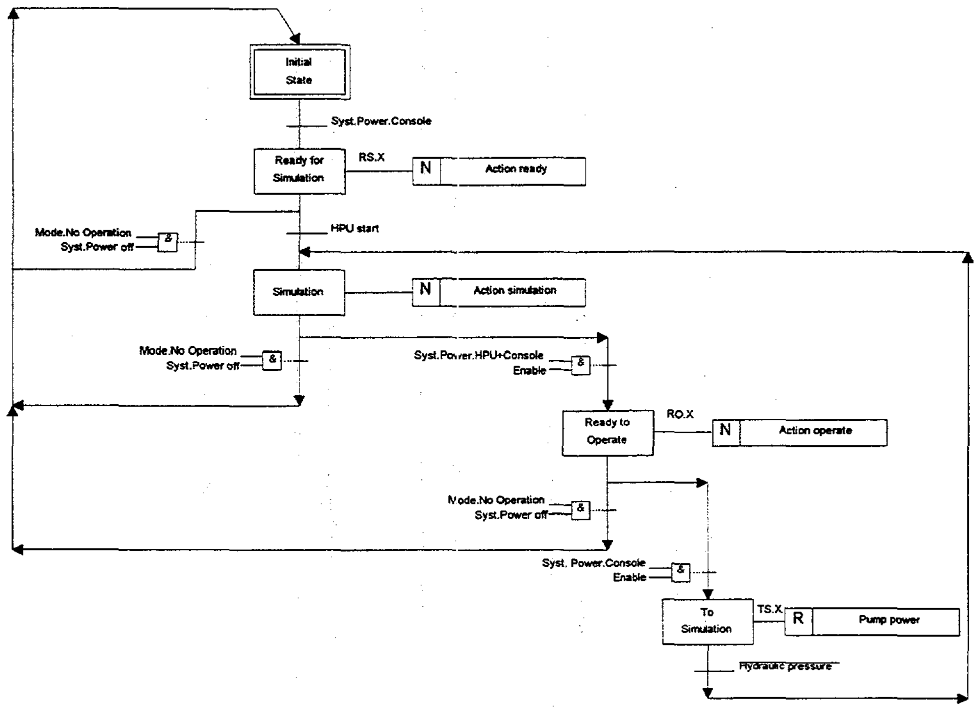


Figure 5.7 Overall control system function chart

If the MODE SELECT switch is in No Operation position, System Power switch turns to Off and confirmed with function Enable, the system will return to initial state. If the mode switch System Power is switched to Console and confirmed with function Enable, the system is going to simulation mode, the power to HPU pump will be cut. When the system hydraulic pressure disappears, the system is ready to start simulation sequence.

2. Typical function chart for simulation and sub-section

If we compare Figure 5.9 with Figure 5.10, we will find that these two charts are almost identical. That is because we want the simulation system can mimic the operation procedures.

The simulation part of control system (Figure 5.9) starts from its initial state. If simulation mode is set (S.X), simulation mode indicator indicates this mode. If the mode switch System Power is switched to HPU+Console and confirmed with function Enable, the simulation system returns to its initial state and waits for further instruction. If the operation mode is set (O.X), the system is ready to start the operation sequence (Figure 5.10). If the MODE SELECT switch is in No Operation position, System Power switch turns to Off, the simulation system will return to its initial state.

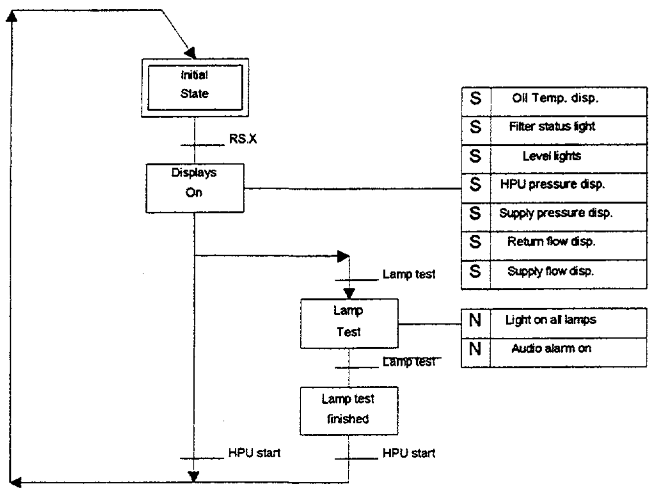


Figure 5.8 Function chart for Action ready sub-function

The operation part of control system (Figure 5.10) starts from its initial state. If operation mode is set (O.X), then operation mode indicator indicates this mode. If the mode switch System Power is switched to Console and confirmed with function Enable, the operation system returns to its initial state and waits for further instruction. If the simulation mode is set (S.X), then the system is ready to start the simulation sequence (Figure 5.9). If the MODE SELECT switch is in No Operation position, System Power switch turns to Off, the simulation system will return to its initial state.

If the MODE SELECT switch is in either Deployment & Pull-in Mode or Connection Mode, all the functions in Common function group and Deployment & Pull-in Mode or Connection can be activated respectively. Each function will act according to function button sequence (Figure 5.12).

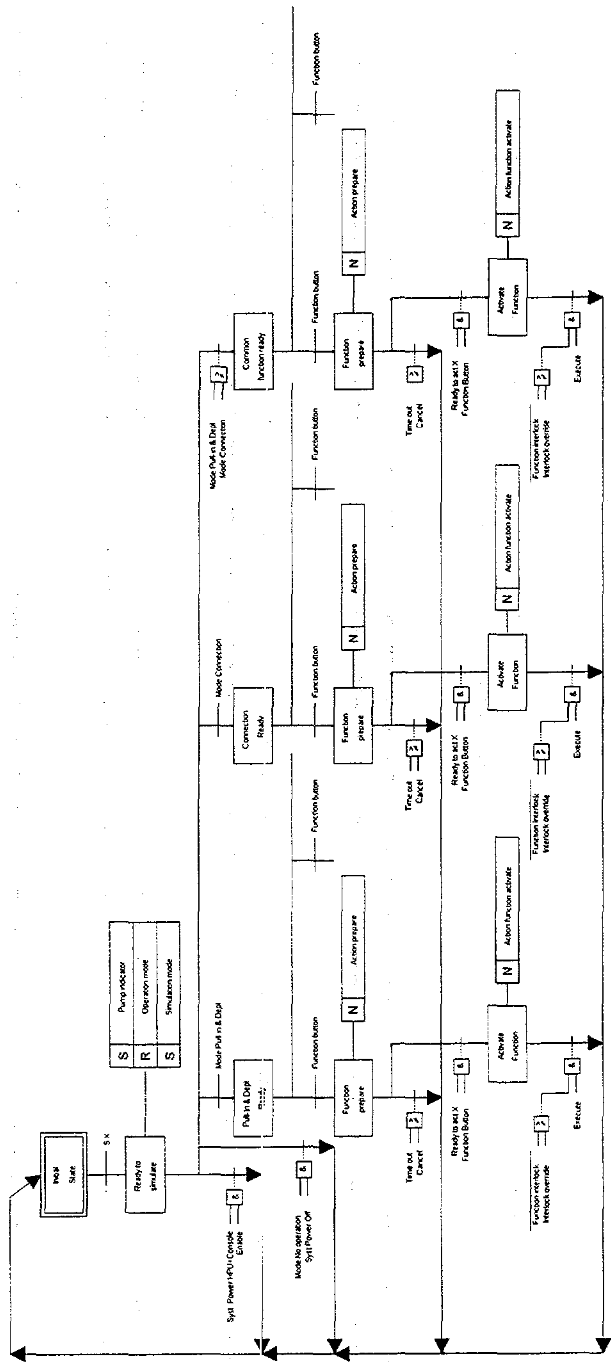


Figure 5.9 Function chart for simulation sub-section

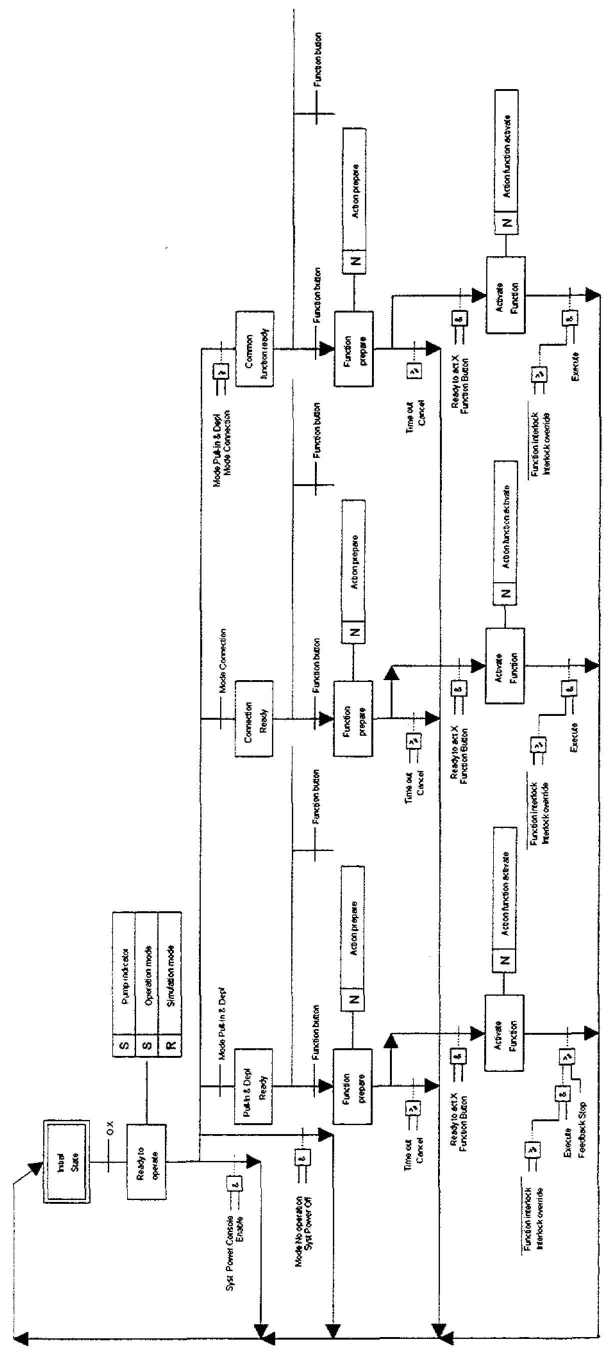


Figure 5.10 Function chart for operation sub-section

3. Typical single function control sequence

Certain procedure should be followed in order to execute an instruction in a safe manner. Some other function should also be contained in the console design in order to help the operator to work easier and more correct. Steps should be designed as such the operator will not be overloaded but still remain sufficient concentration.

From the procedure requirement of a control action, we can construct a part of typical control system as follows:

The panel consists function button, indication light, warning light, cancel/reset, confirmation and override button. On screen message and label are available for different button or light.

Many of the procedure requirements are for the overall system, such as interlock between functions, critical status of individual function, faulty detection and off-line test. Those controls will be part of the system design, so we are not going to describe that in detail. The control of indication light or on screen message can be implement in detail system design, we are not going into detail on this.

A typical control sequence can be defined on the basis of the procedure requirements shown in Figure 5.11 and Figure 5.12.

At the initial state, the current status will be displayed, other indication will be off. The current status can be presented in form of label on or beside light, on screen message.

When the function button is selected, the system will indicate current status by means of light flushing or on screen message such as "Function is activated". The timer is set and interlock status is checked. If interlock persist, the interlock indication will be activated. You can cancel the function by press CANCEL button, the sequence will be terminated and back to initial state. If in special situation, even interlock is persist, the operation requires sequence continue, then we have to use both EXECUTE and INTERLOCK OVERRIDE control to force the awareness of operator.

Besides the checking of interlock status, we have to verify the importance of individual function, if the function is defined as "critical", then the operator should pay special attention to activate it. So if a function is found "critical", the critical indication will be activated, the operator can either cancel by use CANCEL, or use both EXECUTE and CONFIRM CRITICAL to force the awareness of operator.

If the function is a normal function without interlock, then the operator can simple press EXECUTE to activate the function. The function is now ready to activate the actuation device. At this stage, the system still gives operator the last opportunity to stop the sequence. The operator can use CANCEL to stop the sequence or by re-select the function button to set the system in action. The status indication will indicate the current system status, all the warning light will be switch off and indication light or message will show the actuation status.

The whole sequence to activate the system has to be finished within a predefined time interval, for example 60 seconds. If the sequence is not completed within this time interval, a time out command will be issued and the sequence will be terminated.

To stop the system actuation, a new sequence will be followed:

The system can be stopped by the feedback signal from sensors located at actuator(s), then the system status will be set to new initial state. All the variable will be reset, and status indication will reflex the current status (position of actuator, direction of next movement, etc.).

The system can also be stopped by the operator activating the function button. The light on button or on screen message will indicate the selection. The interlock status check is performed. If interlock is persist, the warning indication will be activated (light or message). The operator can either cancel the action by using CANCEL button, or use EXCUTE and INTERLOCK OVERRIDE control to force the awareness of operator.

If no interlock exists, the operator can either cancel the action by using CANCEL button or EXECUTE.

The whole sequence will be completed by re-select the function button to stop the system. The function will be stopped, and the system is set to initial state.

The stop sequence has also to be completed within the predefined time scale, otherwise the system time out, and back to the previous state (Actuation).

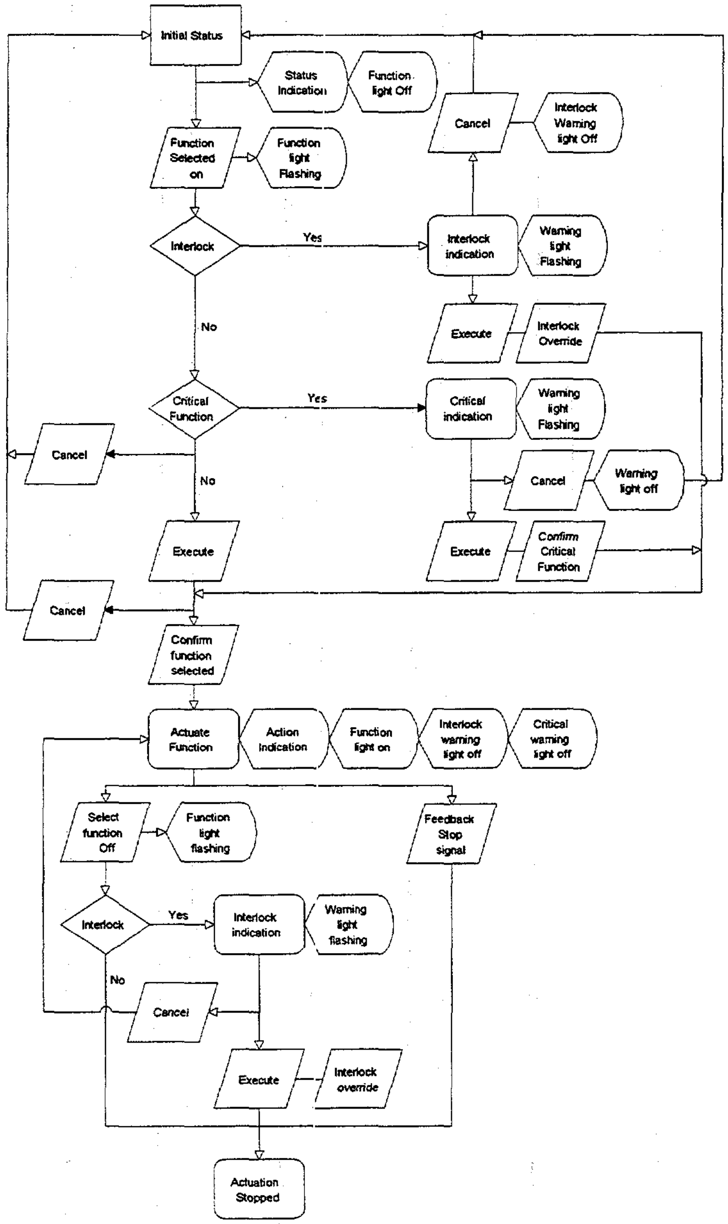


Figure 5.11 Typical Flow Chart for a tool function Control

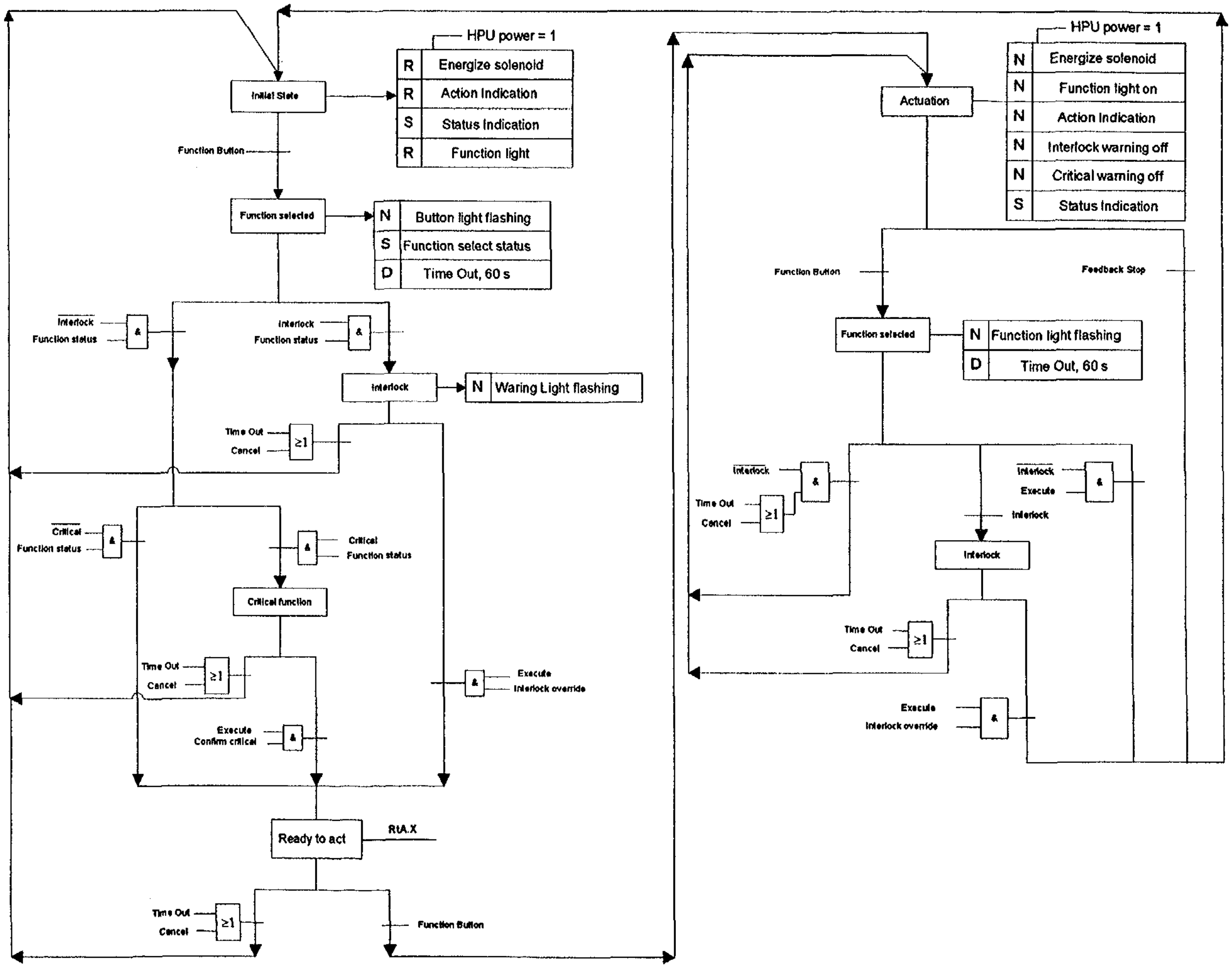


Figure 5.12 Function chart for a typical control function

5.4 Ergonomic analysis criteria for control system

A good system design should include not just fulfill the functionality requirement, if the system design has not operator in mind, then the performance will not be optimal. Much effort has been devoted to find out the best possible working condition.

5.4.1 Surface control systems

To run a task under the best possible conditions, the operator must not tire mentally or physically too quickly. To avoid these effects the control system must be adaptable to the human form, both with respect to posture and the movements and forces to be exerted. In addition, the feedback signals received by the operator must not exceed a certain rate and should be relevant to the application. At the same time they must be in a form that minimizes the amount of thought and attention required from the operator. Following sections summarize some of the ergonomic related criteria for surface equipment.

5.4.2 Working environment

Control tasks demand the operator's long time concentration, calm decision making and stable action. Therefor the result can various a lot depending on the working condition. The primary working condition for the operator is the lighting and ventilating condition in the control room. Color of the light, temperature and noise level also can have significant effect on the result of operator. Many researches have been done on those subjects. The following lists some of the result they obtained.

Table 5.14 Environment requirement in control room

	Ergonomic Consideration	Recommendation
1.	Illumination	
	a. No hardcopy	300 lux
	b. With normal hard copy	500 lux
	c. Environmental luminance contrast	
	Near objects	1:3
	Far objects	1:10
2.	Heating, Ventilating and Air Conditioning	
	a. Temperature-winter	20°-24°C (68°-75°F)
	b. Temperature-summer	23°-27°C (73°-81°F)
	c. Humidity	50-60%
	d. Airflow	0.15-0.25 m^3/sec
3.	Color of light	
	Good temperature regulating	Reddish-pink/Orange
	Nature ventilation (closed door)	Yellow/Pale blue
4.	Noise level	< 70dB

5.4.3 Safety

Safety is always one of the most important problem. In any system design, non of the product is assumed to harm the operator or other personnel in any circumstance. If hazard exists in some situation, precaution should be taken to avoid such situation from occurring. A check list has been made to assist designer in issues related to safety.

Figure 5.13 Check list for safety consideration

	Safety issue	Item to be checked
1.	Hazard to operator	"What if" check
2.	Hazard to other personnel	"What if" check
3.	Fire	Fire and Smoke alarm Fire distinguish equipment
4.	Gas	Gas detection
5.	Emergency Exit Channel	Size should be enough for 5% to 95% people size Location should be easy to access
6.	Emergency Door	Way of open should not depend on other means
7.	Power failure	Emergency light, safety procedure to keep tool system in a safe status, UPS (Un-interruptible power supply) capable of operating the control system for a specified length of time

5.4.4 Space

The operator should have adequate working space, otherwise the operator will not be able to keep up the highly loaded operation.

The space in a control room is limited, however, with carefully design, space will be available for all the important functions.

The one of the most important issue is the design of control table. Combining the arrangement of chair, the control table should be able to fit the size for most of people group. The height should not consideration large size operator only, it should also consider the smaller size operator.

Most of the operations will take a certain length of time, so space for drink and operation reference manual should also be reserved. Table 5.15 lists some of the conclusions from ergonomic research regarding control table size and chair (ref. chapter four).

Table 5.15 Work space related requirement

	Item	Requirement
1.	Control table	
	a. Leg clearance b. Leg depth c. Leg depth with leg extension d. Work surface height-nonadjustable	51 cm minimum (61 cm preferred minimum) 38 cm minimum 60 cm minimum
2.	Chair	
	a. Seat pan width b. Seat pan depth c. Seat front tilt d. Seat back inclination e. Backrest height	45 cm minimum 38-43 cm minimum 5° forward to 7° backward 110°-130° 45-51 cm
3.	Table space	Space for operation manual Position for cup holder

5.4.5 Feedback and internal communication on control panel

The operation and system status information is crucial for the operator to make a good decision, so feedback signals need to be displayed on control panel. Intercom system for communicating with other part of system should also be included.

Table 5.16 Required Feedback on control panel

System variable/function	Information type	Acquisition method
Pressure of hydraulic system		Pressure gauge/transducer
Reservoir level indication	Position	
High temperature	Temperature	
Gas/Fire		
Filter status	Pressure difference	
System flow	Flow	
Pump pressure	Pressure	Pressure gauge/transducer
Interlock indication	Flag	Internal Flag
Critical function indication	Flag	Internal Flag
Tool Lock down	Position	Position sensor
Pull-in Winch	Pressure/Position	Pressure transducer/Position sensor
Connector Latch	Position	Position sensor
Connector Elevator	Position	Position sensor
Connector make up	Position	Position sensor

5.5 Control system for Pull-in and Connection Tool

5.5.1 Pull-in and Connection Tool (PICT)

The Pull-in and Connection Tool (PICT) is a combined tool which does both pull-in and connection in the same run. Main dimensions are 3.21 x 1.6 x 4.35 m, and the weight is approximately 10 tons.

The function of the Kværner's PICT is to provide for the combined operations of termination pull-in and connection. The functions of pull-in and connection may be performed in a single run or two separate runs, thus greatly reduced deployment time yet kept maximum flexibility.

PICT Connection abilities include Main ISU bundles, Infield ISU bundles, Gas Lift Module Lines, Gas Lift ISU Connections, Pipe lines of 6" and 8" ID's, and Gathering Lines and Risers of 9" and 10" ID's. The design pressures range vary up to 345 bar, depending on the connection application. Pigging requirements are met where applicable.

The PICT is designed as a compact, lightweight tool for flexible line tie-ins in rough offshore environments, with all of the tool components lying inside the protective frame envelope. Its primary aim is to reduce operational time and cost. The PICT is designed to connect and establish leakproof mechanical clamp type connections for various horizontal pipe lines and ISU (Integrated Service Umbilical) bundles. It is designed as a remote operated unit, no divers are required.

Design depth of the Pull-In and Connection Tool (PICT) is 350 meters; the design life time is 27 years.

5.5.2 Main sub-systems for PICT

The Pull-in and Connection Tool (PICT) consists of following main systems:

- **Main Frame** comprises the strength members and function as the support for all the other sub-systems of the tool. The main frame has a central pad eye for lifting by the lifting wire.
- **Guide funnels** for two guidewires with standard spacing for guiding the tool onto the two guideposts.
- **Lock down System** connects the PICT to the subsea porch structure on the miniposts.
- **Wire Feeding System**. The pull-in wire is equipped with a stab-in wire anchor which is located in a bracket in front of the tool during running. The ROV to bring the wire anchor out and to stab the anchor into the pull-head while the wire is fed out by the wire feeder.
- **Linear Winch** provides up to 30 t pull-in force in the pull-in wire. The wire goes through the linear winch up to a take-up reel on surface. Both first and second end pull-ins can be done by this set up.
- **Receiver funnel** provides alignment and orientation of the termination during the pull-in operation. The Receiver Funnel is tilted during pull-in and brings the termination to a horizontal plane for connection. The Receiver Funnel is split with two hatches in the bottom allowing the funnel to be retrieved together with the tool.

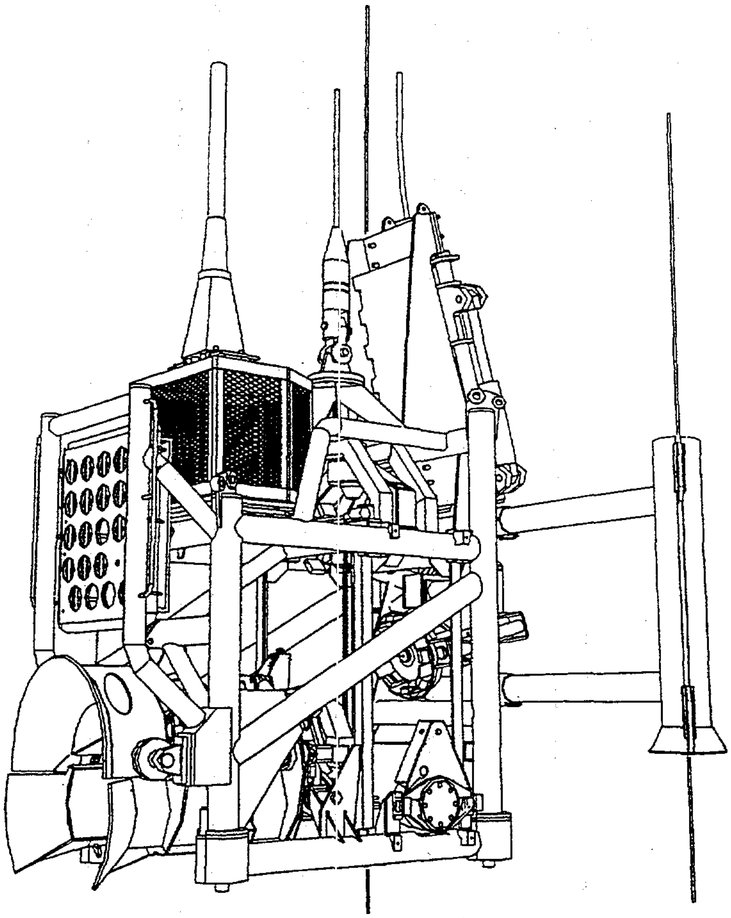


Figure 5.14 The main structure of Kværner's PICT

- **Pullhead receiver** takes the pullhead off the termination and stores the pullhead for retrieval.
- **Stroking Cylinders** with horse shoe bring termination back and forth during the tie-in operation.
- **Elevator System** keeps the Clamp Connector out of way during pull-in and brings it in between the hubs for connection. The Clamp Connector is held into the elevator by the male stab and a collect connector. Back seal test of the clamp connector can be performed.
- **Torque tools** operate the Clamp Connector Screw to make up the Clamp.

- **ROV panel** allows the ROV to operate the PICT if any failure occurs during the operation. All functions have mechanical and/or ROV override possibilities to allow retrieval of the PICT in case of failure.

Figure 5.14 is the main structure of the combined pull-in and connection tool (PICT) by Kværner Energy a.s for Norsk Hydro's Troll Olje project.

The PICT is designed with accumulator assistant which can perform the necessary functions to suspend pull-in and connection operations in case of hydraulic power loss. ROV Intervention control is provided along with the accumulator reserves with ROV Mechanical Intervention capability provided for emergency tool release.

The control system used by Troll Olje Tie-in project is a pilot operated all-hydraulic control. The whole system consists both surface devices and subsea devices. The general arrangement of this intervention control system (ICS) shows in Figure 5.15.

5.5.3 Intervention Control System (ICS)

The Intervention Control System (ICS) is based on direct hydraulic and pilot hydraulic signal transmissions (Figure 5.15).

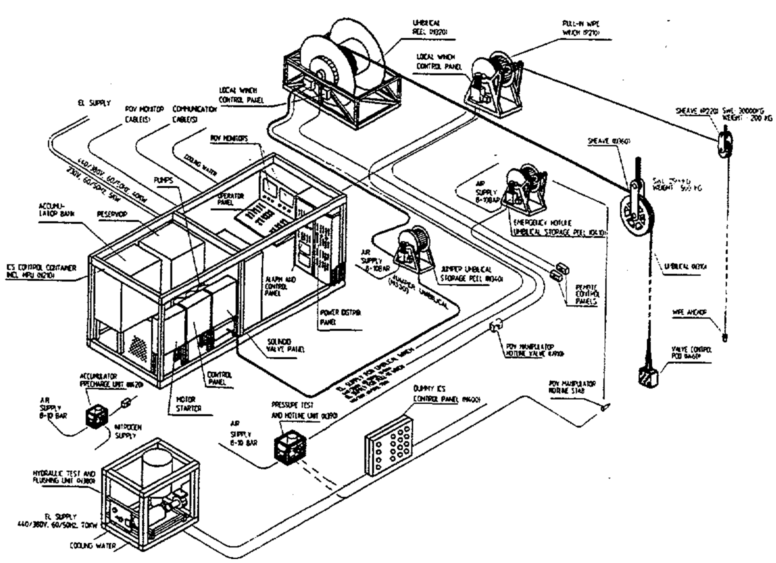


Figure 5.15 General arrangement of Intervention Control system for PICT

The ICS container at surface has an operator panel with electrical push buttons for all tool functions. A PLC controls the signals and defines interlocks to prevent wrong or critical functions to be performed. A solenoid valve pack is located in the Hydraulic Power Unit (HPU) which gives hydraulic power to the different pilot lines. On the PICT a valve pod is located where pilot signals open valves to the actual hydraulic cylinder with supply from the main supply header.

This type of control system was selected to avoid electronics subsea. The equipment can be repaired by service personnel offshore.

Owing the fact that PICT and parts of the ICS works submerged in sea water, the risk of water intrusion into the fluid conduit system may not be excluded. The system will be stored for onshore for long periods over its 27 years design life and under conditions being unfavorable with respect to corrosion. For optimal protection all line equipment shall as a minimum be made of stainless steel to quality AISI 316 or of other adequate non corroding materials. Also other hydraulic fluid conducting or containing components shall take these aspects into account when being selected or designed, to obtain proper protection by material selection or adequate protective measures.

The Intervention Control System (ICS) is used to power, control and monitor the combined Pull-in and Connection Tool. It includes the following:

- ICS control Container and Tool Mounted Valve Module complete with:
    * Hydraulic Power Unit (HPU)
    * Master Control Station (MCS)
    * Power Distribution Unit (PDU)
    * Purging System
    * Lighting, heating and ventilation
    * Tool Mounted Subsea Valve Module
    * Operator control panel
- Umbilical System.
    * Umbilical Reel
    * Umbilical with termination
    * Jumper Umbilical with termination
    * Jumper Umbilical storage reel
- Test and Auxiliary Equipment

5.5.4 Control functions and sequences for PICT

5.5.4.1 Control functions and control signals

From the analysis of the task, the typical operation sequence in Table 5.2 and the mechanical construction of the equipment (Figure 5.14), we can find that the following functions (Table 5.17) are needed to be controlled. Default states and command activated states are determined by the nature of the mechanical arrangement of the PICT.

PICT system consists mechanical frame, actuators, hydraulic valve block, umbilicals and hydraulic power system (HPU) with solenoid valves.

Table 5.17 PICT function names and status

FUNCTION NAME	FUNCTION STATUS NAME			
	Default state	Command activated state		
Tool Lock Down	Lock	Unlock		
Funnel Tilt	Hold	Horizon.	Tilt	Float
Termination Stroke	Hold	Stroke	Retract	Float
Connector Latch	Mech. Lock	Unlock	Lock	

FUNCTION NAME	FUNCTION STATUS NAME			
	Default state	Command activated state		
Funnel Hatch	Close	Open		
Cramp Wedge	In	Retract		
Cramp Bolts	Out	In		
Pullhead Receiver	Retract	Extend		
Wire Feeder	Float	On		
Pull Ram	Hold	Retract	Pull	Auto
Pull Prepare	Max. Speed	Slow Speed		Apply
Grippers	Open/Close	Open	Close	
Connector Elevator	Float	Up	Down	
Torque Tool Make	Float	Auto		
T.T. Engage Make	Out	In		
Torque Tool Break	Float	Auto		
T.T. Engage Break	Out	In		
Center box	Float	Disconnect	Connect	
Seal Test	Off	Test		

In order to reduce the number of hydraulic pilot lines needed to operate the system and remain flexible, the control system groups the tool functions into three groups – Common functions, Pull-In and Deployment mode and Connection mode. A switch valve block is used to control between different operation mode. The pilot lines are shared between pull-in mode and connection mode functions, and two pilot signals P_P and P_C are used to select among these two modes.

The valves on the valve block are controlled by hydraulic pilot signals from surface via umbilical. A set of solenoid valves is controlled by PLC. Table 5.18, Table 5.19 and Table 5.20 list function name, state of the function, actuator and the solenoid control signals. The solenoid signal combination gives a Truth table for that function. The unlisted combinations of solenoid signal are not allowed.

Pull-In and Deployment mode consists all the functions used only during pull-in operation, deployment and retrieval of the tool. Connection mode consists all the functions used only during connection operation. Common functions are the ones can be activated during either mode.

The solenoid names used in the tables are from the actual hydraulic schematic diagram. This schematic diagram is not part of attachment of this document.

Table 5.18 Common functions

FUNCTION NAME	SOLENOID			STATE	ACTUATOR
Tool Lock Down	E1				Double rods cylinders with ROV mechanism
	1			Unlock	
	0			Lock	
Funnel Tilt	E2	E3	E_{SP1}		Single rod cylinder group
	0	0	0	Hold	

FUNCTION NAME	SOLENOID			STATE	ACTUATOR
	1	0	0	Tilt	
	0	1	0	Horizontal	
	0	0	1	Float	
Termination Stroke	E4	E5	E6		Single rod cylinder
	0	0	0	Hold	
	1	0	0	Stroke	
	0	1	0	Retract	
	0	0	1	Float	
Connector Latch	E7	E8			Double rods cylinders
	0	0		Mech. lock	with ROV mechanism
	1	0		Lock	
	0	1		Unlock	

Table 5.19 Deployment and pull-in mode (E_P=1)

FUNCTION NAME	SOLENOID				STATE	ACTUATOR
Funnel Hatch	E9					Single rod
	1				Open	cylinders
	0				Close	
Cramp Wedge	E10					Single rod
	1				Retract	cylinder
	0				In	
Cramp Bolts	E11					Double rods
	1				In	cylinders
	0				Out	
Pullhead Receiver	E12					Double rods
	1				Extend	cylinders
	0				Retract	
Wire Feeder	E13					Motor
	1				On	
	0				Float	
Pull Ram	E14	E15	E16			Single rod
	0	0	0		Gripp. float	cylinder
	0	0	1		Apply	
	1	0	1		Pull	
	0	1	1		Retract	
Slow Speed	E11	E14	E15	E16		
	0	0	0	0	Gripp. float	
	0	0	0	1	Apply	
	1	1	0	1	Slow Speed	
	0	0	1	1	Retract	
Grippers	E16	E17	E18			Single rod

FUNCTION NAME	SOLENOID				STATE	ACTUATOR
	0 0 0 1	0 1 0 0	0 0 1 0		Floating Open Close Apply	cylinders

Table 5.20 Connection mode (E_C=1)

FUNCTION NAME	SOLENOID			STATE	ACTUATOR
Connector Elevator	E9 0 1 0	E10 0 0 1		 Float Down Up	Motor
Torque Tool Make	E14 1 0			 Auto Float	Single rod cylinder
T.T. Engage Make	E12 1 0			 In Out	Double rods cylinder
Torque Tool Break	E15 1 0			 Auto Float	Single rod cylinder
T.T. Engage Break	E11 1 0			 In Out	Double rods cylinder with ROV mechanism
Center Box	E13 0 1 0	E17 0 0 1		 Float Disconnect Connect	Double rods cylinder

5.5.4.2 Interlock table and functions

The following tables (Table 5.21 to Table 5.25) are the interlock status table between different functions.

By pressing a function button (function flow chart in Figure 5.12), the PLC are checking the states against all the other functions. If the PLC find an interlock state to the other functions, the reply is an interlock warning on the actual interlocking function(s).

A typical example for this is the "Funnel Tilt" function.

If the “Funnel Tilt” function is in or on the way to "Horizontal" position, it shall not be possible to perform Wire Feeder "ON", without override an interlock warning.

The tables are not listed according to the operational sequences, but the relationship between functions.

Table 5.21 Interlock table in Deployment & Pull-in mode

FUNCTION		Function not allowed			
		Tool lock down	Funnel tilt	Funnel tilt	Termination stroke
		Unlock	Tilt	Horizon	Stroke
Tool Lock Down	Unlock				
	Lock				
Funnel Tilt	Tilt				
	Hold				
	Horizon.				
	Float				
Termination Stroke	Stroke			X	
	Hold				
	Retract				
	Float				
Connector Latch	Unlock				
	Mech. Lock				
	Lock				
Funnel Hatch	Open		X	X	
	Close				
Cramp Wedge	Retract	X	X		X
	In				
Cramp Bolts	In		X	X	
	Out				
Pullhead Receiver	Extend				
	Retract				
Wire Feeder	On				
	Float				
Pull Ram	Auto				
	Hold				
	Pull				
	Retract				
Pull Prepare	Apply				
	Off				
	Slow Speed	X		X	
	Off				
Grippers	Open				
	Floating				
	Close				

Table 5.22 Interlock table in Deployment & Pull-in mode (Cont.)

FUNCTION		Function not allowed			
		Connector Latch	Funnel hatch	Cramp wedge	Wire feeder
		Unlock	Open	Retract	On
Tool Lock Down	Unlock				
	Lock				
Funnel Tilt	Tilt	X	X	X	

FUNCTION		Function not allowed			
		Connector Latch	Funnel hatch	Cramp wedge	Wire feeder
		Unlock	Open	Retract	On
	Hold				
	Horizon.				X
	Float				
Termination Stroke	Stroke			X	
	Hold				
	Retract				
	Float				
Connector Latch	Unlock				
	Mech. Lock				
	Lock				
Funnel Hatch	Open				
	Close				
Cramp Wedge	Retract				
	In				
Cramp Bolts	In			X	
	Out				
Pullhead Receiver	Extend	X			
	Retract				
Wire Feeder	On				
	Float				
Pull Ram	Auto				
	Hold				
	Pull				
	Retract				
Pull Prepare	Apply				
	Off				
	Slow Speed			X	
	Off				
Grippers	Open				
	Floating				X
	Close				X

Table 5.23 Deployment & pull-in mode (Cont.)

FUNCTION		Function not allowed			
		Pull ram	Pull ram	Pull ram	Pull prepare
		Auto	Pull	Retract	
Tool Lock Down	Unlock				
	Lock				
Funnel Tilt	Tilt				
	Hold				
	Horizon.	X	X	X	X
	Float				
Termination Stroke	Stroke				
	Hold				
	Retract				
	Float				
Connector Latch	Unlock				
	Mech. Lock				
	Lock				

FUNCTION		Function not allowed			
		Pull ram	Pull ram	Pull ram	Pull prepare
		Auto	Pull	Retract	
Funnel Hatch	Open Close				
Cramp Wedge	Retract In				
Cramp Bolts	In Out				
Pullhead Receiver	Extend Retract				
Wire Feeder	On Float				
Pull Ram	Auto Hold Pull Retract				
Pull Prepare	Apply Off Slow Speed Off	X	X	X	
Grippers	Open Floating Close				

Table 5.24 Interlock table in Connection mode

FUNCTION		Function not allowed			
		Funnel tilt	Termination stroke	Connector latch	Connector elevator
		Tilt	Retract	Unlock	Down
Tool Lock Down	Unlock Lock				
Funnel Tilt	Tilt Hold Horizon. Float			X	X
Termination Stroke	Stroke Hold Retract Float				
Connector Latch	Unlock Mech. Lock Lock				
Connector Elevator	Up Float Down			X	
Torque Tool Make	Auto Float				
T.T. Engage Make	In Out	X	X		
Torque Tool Break	Auto				

FUNCTION		Function not allowed			
		Funnel tilt	Termination stroke	Connector latch	Connector elevator
		Tilt	Retract	Unlock	Down
	Float				
T.T. Engage Break	In Out	X	X		
Center Box	Disconnect Float Connect				

Table 5.25 Interlock table in Connection mode (Cont.)

FUNCTION		Function not allowed			
		T.T. Engage make	T.T. Engage break		
		In	In		
Tool Lock Down	Unlock Lock				
Funnel Tilt	Tilt Hold Horizon. Float				
Termination Stroke	Stroke Hold Retract Float				
Connector Latch	Unlock Mech. Lock Lock				
Connector Elevator	Up Float Down				
Torque Tool Make	Auto Float				
T.T. Engage Make	In Out		X		
Torque Tool Break	Auto Float				
T.T. Engage Break	In Out	X			
Center Box	Disconn. Float Connect				

From the interlock tables, we can develop a table of interlock functions, the PLC can use the logic functions as the input for the interlock state checking. When the result of the function is TRUE, a flag of "Interlock exists" will be set and a warning signal will be issued.

Table 5.26 Interlock function

FUNCTION		Interlock Functions
Tool Lock Down	Unlock Lock	
Funnel Tilt	Tilt Hold Horizon. Float	(E8) V ((E9 V E10 V E11) & (EP)) V (E9 & EC) (E13 V E10 V E11 V E15 V E16) & (EP)
Termination Stroke	Stroke Hold Retract Float	(E3)
Connector Latch	Unlock Mech. Lock Lock	
Funnel Hatch	Open Close	(E2 V E3)
Cramp Wedge	Retract In	(E1 V E2 V E4)
Cramp Bolts	In Out	(E2 V E3) V (E11) & (EP)
Pullhead Receiver	Extend Retract	(E7)
Wire Feeder	On Float	
Pull Ram	Auto Hold Pull Retract	
Pull Prepare	Apply Off Slow Speed Off	 ((E14 & E16) V (E15 & E16)) & (EP) (E1 V E3) V ((EP) & (E10))
Grippers	Open Floating Close	 E13 & EP E13 & EP
Connector Elevator	Up Float Down	E10 & EC
Torque Tool Make	Auto Float	
T.T. Engage Make	In Out	E2 V E5 V (E11 & EC)
Torque Tool Break	Auto Float	
T.T. Engage Break	In Out	E2 V E5 V (E12 & EC)
Center Box	Disconn. Float Connect	

5.5.4.3 Operational procedure

1. Typical Sequence for Tie-in operation with mechanical tie-in tool

To ensure a successful tie-in operation by using mechanical tie-in tool, a pre-defined operation procedure must be followed. The procedure is represented by a set of sequences. The sequences are carefully defined after analysis of mechanical structure of the tool and marine operation requirements.

The typical procedure of complete tie-in operation can be split into four phases, each phase consists many steps, and each step consists some actions.

The tool is built for conducting a variety of tasks. Besides the ordinary tie-in operation, the tool can also carry out tasks as replacing Clamp Connector, performing pull-in and connection separately, installing and retrieval of Pig Launcher and retrieval of Blind Cap. These typical sequences are used for the ordinary tie-in operation, to illustrate how the different functions are linked together.

Table 5.27 lists the typical sequence for initializing a tie-in operation. The sequence starts from returning all functions to their default state. The connector will be loaded afterwards. When all the preparation actions are finished, the tool is ready to be deployed. With the help of surface lifting tool, the tool is lowered on to the subsea structure, and then locked on to structure by its own mechanism.

Table 5.28 lists the typical sequence for pull-in and to secure a flowline. The sequence starts from adjusting the funnel to tilt position, the tilted position eases the entering force for the flowline. With the help of ROV, the pull-in wire is connected to the pullhead which is pre-installed on the termination hub on the flowline. The linear winch starts to pull the wire until the termination is very close to the funnel. The pull speed is reduced for safety reasons. After the termination reached the pullhead receiver, the pullhead is released in the receiver and held by the retracting the Linear Winch to the end position. At the end, the funnel is tilted to horizontal position. The pull-in sequence is now completed.

Table 5.29 lists the typical sequence for connecting the termination by the clamp connector. The sequence starts from adjusting the position of the connector, then the elevator is lowered with connector. Termination stroke pushes the termination against connector and the inboard hub. The Torque Tool is engaged and starts tightening sequence. After the designated torque is reached, the torque tool is stopped. The Torque Tool then is disconnected. A seal test is carried out to verify the tightness of the connection. When the test is passed, the Connector Latch releases the connector, and the Connector Elevator returns to top position. The connection sequence is not completed.

Table 5.30 lists the typical sequence for retrieval of the tool. The sequence starts from securing the pullhead by close the grippers on the Linear Winch, the Termination Stroke is put into float state. The Funnel Hatch is force to open if it is not already opened. Tool lock down mechanism is opened and the tool is lifted from the subsea structure and then retrieved to surface.

Table 5.27 Typical sequence for load connector and deploy the tool

No.	Tool Function/Activity	Button Name	Press Button	Confirm Execute	Function State
1	Turn Mode Switch to Deployment & Pull-In Mode				
2	Termination Stroke/ Bring Horse shoe in retracted position	Retract	X	X	Retract
3	Termination Stroke/ Lock the function in position	Retract	X		Off
4	Funnel Tilt/ Bring the funnel in horizontal position	Horizon	X	X	Horizon
5	Funnel Tilt/ Lock the function in position	Horizon	X		Off
6	Center Box/ Bring the center box against funnel	Disconn.	X	X	Disconn
7	Center Box/ Bring the center box in float position	Disconn.	X		Off
8	Connector Latch/ Bring the locking dogs in open position	Unlock	X	X	Unlock
9	Connector Elevator/ Run the elevator down to the connector transport box	Down	X	X	Down
10	Connector Elevator/ Stop the elevator	Down	X		Off
11	Connector latch/ Close the latches on the new connector	Lock	X	X	Lock
12	Connector elevator/ Run the elevator with connector to top position	Up	X	X	Up
13	Connector elevator/ Stop the elevator at position	Up	X		off
14	Grippers/ Lock the wire in connect position	Close	X	X	Close
15	Grippers/ Keep the grippers at closed position	Close	X		Off
16	Tool Lock Down/ Open the tool locking mechanism	Unlock	X	X	Unlock
17	Lift the tool off the porch				
18	Tool Lock Down/ Locking mechanism returns to locked position	Unlock	X		Off
19	Turn Mode Switch to NO OPERATION				
20	Deployment of tool				
21	Turn the Mode Switch to Pull-In & Deployment Mode				
22	Grippers/ Secure the wire	Close	X	X	Close
23	Tool Lock Down/ Open the tool locking mechanism	Unlock	X	X	Unlock
24	Tool Lock Down/ Locking the tool after lowering it down the porch	Unlock	X		Off
25	Grippers/ Release the grippers	Close	X		Off/ Ready to start Pull-In

Table 5.28 Typical sequence for Pull-In Operation

No.	Tool Function/Activity	Button Name	Press Button	Confirm Execute	Function State
1	Funnel Tilt/ Bring the funnel to tilted position	Tilt	X	X	Tilt
2	Funnel Tilt/ Stop the funnel in position	Tilt	X		Off
3	Grippers/ Open the grippers	Open	X	X	Open
4	Wire Feeder/ Start feeding wire	On	X	X	On
5	Wire Feeder/ Stop feeding wire	On	X		Off
6	Wire to be connected to pullhead				
7	Grippers/ Release the grippers	Open	X		Off
8	Pull Prepare/ Grippers activated with spring pressure	Apply	X	X	Apply
9	Pull Ram/ Start pull-in with Linear winch	Auto	X	X	Auto
10	Pull Prepare/ Reduce the pull speed before entering the funnel	Slow Speed	X	X	Slow speed
11	Pull Ram/ Stop the Linear winch after entering horse shore bolts	Auto	X		Auto
12	Termination stroke/ Bring the stroke cylinders in float mode	Float	X	X	Float
13	Pull Ram/ Prepare the Linear winch for a full stroke	Retract	X	X	Retract
14	Pull Ram/ Pull the flowline one stroke	Pull	X	X	Pull
15	Pull Ram/ Prepare the Linear winch for a full stroke	Retract	X	X	Retract
16	Pull Ram/ Pull until stroke cylinders are fully stroked	Pull	X	X	Pull
17	Pull Ram/ Prepare the Linear winch for a full stroke	Retract	X	X	Retract
18	Termination Stroke	Float	X		Off
19	Pullhead Receiver/ Release of Pullhead	Extend	X	X	Extend
20	Pull Ram/ Bring pullhead and receiver back to safe position	Pull	X	X	Pull
21	Grippers/ Secure the pullhead in position	Close	X	X	Close
22	Pull prepare/ Turn off grippers spring pressure	Apply	X		Off
23	Pull Prepare/ Turn off Slow speed function	Slow speed	X		Off
24	Termination Stroke/ Bring horse shore and flowline back to safe position	Retract	X	X	Retract
25	Termination Stroke/ Lock the stroke cylinders in position	Retract	X		Off
26	Funnel Tilt/ Tilt the funnel to horizontal position	Horizon	X	X	Horizon
27	Funnel Tilt/ Lock the funnel in horizontal position	Horizon	X		Off
28	Grippers/ Turn off the grippers close pressure	Close	X		Off
29	Turn Mode switch to Connection Mode				Ready to connect

Table 5.29 Typical Sequence for Connection operation

No.	Tool Function/Activity	Button Name	Press Button	Confirm Execute	Function State
1	Center Box/ Bring the center and connector in position	Disconn	X	X	Disconn
2	Center Box/ Set the center box in float position	Disconn	X		Off
3	Conenctor Elevator/ Run the elevator and connector down to position	Down	X	X	Down
4	Connector Elevator/ Stops the elevator in position	Down	X		Off
5	Termination Stroke/ Bring the flowline against connector and inboard hub	Stroke	X	X	Stroke
6	Termiantion Stroke/ Stops the stroke cylinders and lock them in position	Stroke	X		Off
7	Torque Tool Make/ Start the torque tool (T.T)	Auto	X	X	Auto
8	Torque tool Engage Make/ Connect the torque tool to the connector	In	X	X	In
9	Torque Tool Make/ Stops the torque tool	Auto	X		Off
10	Torque Tool Engage Make/ Disconnect the torque tool	In	X		Off
11	Perform Seal Test				
12	Conenctor Latch/ Release the connector from the elevator	Unlock	X	X	Unlock
13	Connector Elevator	Up	X	X	Up
14	Conenctor Elevator/ Stop the elevator	Up	X		Off
15	Connector Latch/ Free the Connector latch	Unlock	X		Off
16	Switch to Deployment & Pull-in Mode				

Table 5.30 Typical sequence for retrieval of the tool

No.	Tool Function/Activity	Button Name	Press Button	Confirm Execute	Function State
1	Grippers/ Close the grippers and secure the pullhead	Close	X	X	Close
2	Grippers/ Hold the grippers closed	Close	X		Off
3	Termination Stroke/ Bring the stroke cylinders in float mode	Float	X	X	Float
4	Funnel Hatch/ Open the hatches	Open	X	X	Open
5	Tool Lock Down/ Open the tool locking mechanism	Unlock	X	X	Unlock
6	Pull off the tool from the porch				
7	Termination Stroke/ Turn off the float function	Float	X		Off
8	Funnel Hatch	Open	X		Off
9	Tool Lock Down/ Tool Locking mechanism returns to lock position	Unlock	X		Off
10	Turn the mode switch to NO OPERATION				
11	Retrieve the tool to surface				

5.6 Evaluating control system used in Troll Olje Tie-in equipment

When people start to evaluate a system, a table of functions should be written. The required functions should have is own form, then compare with two forms, pick out the redundant function, put in missing functions, and then re-compare two forms, until the functions required can be fully implemented by the proposed system.

5.6.1 Comparison of control system types

There are basically four types of system can fulfill the requirement of control tie-in equipment in relative deep and deep working depth. Each of them has drawback and advantage over each other. Since all of them can be selected freely in system design, scale factor is applied to them. The criteria listed in Table 5.31 are based on interviews and personal opinions, the same as the scores listed from Table 5.32 to Table 5.35. The resulting scores are calculated on bases of formula in Table 4.3.

Table 5.31 Evaluation criteria for underwater control system (General)

	Criteria	Definition
1.	Reliability, System	Probability of system performs its intended mission without hardware failing. Higher value means less chance to fail.
2.	Reliability, Operation	Probability of operator performs intended mission without failure or serious mistake. Higher value means less chance to mistake.
3.	Reliability, Independence to other equipment	Probability of system performs its intended mission without dependent on other system's status. Higher value means less dependency.
4.	Cost, Operation	Cost of operating system, includes personnel involved. Higher value means less cost.
5.	Control signal, Amount of	Amount of control signals, it corresponds the number of control function. Higher value means more control functions.
6.	Feedback, Amount of	Amount of feedback signals, it corresponds the number of system status variables can be monitored.
7.	Cost, Maintenance	Cost of maintenance the system. Higher value means less expensive and faster maintenance activity.
8.	Cost, Manufacturing	Cost of manufacturing system. Higher value means less expensive in manufacturing.
9.	Response time	Time required to perform one single function. Higher value means faster response.
10.	Energy consumption	Total system energy required for same amount of energy consumed in actuators. Higher value means less total system energy consumed.
11.	Flexibility to modification	Possibility of modify/add control functions. Higher value means easier to modify/add control functions.
12.	Complicity of system	Parts involved in a system. Higher value means more modulated system.
13.	Space requirement	Space needed to place all equipment. Higher value means less space is needed.
14.	Testability	Ability to find out system status. Higher value means easier to find out status of system and locate failure.

1. Direct hydraulic pilot operated valve pod

The principle of Direct pilot discrete hydraulic as we have introduced in chapter 2, the system utilizes hydraulic supply and pilot signal line from surface via flexible hydraulic umbilical. The return fluid is returned to surface. All the control electronic and electrical devices are located on surface vessel, normally within their enclosures. Only pilot controlled hydraulic valves are located subsea. The system gives very good reliability regarding system components; the control interface is relative simple but reliable. When the water depth is moderate, the response time is reasonable short, and performance is acceptable. Since the whole system is powered by hydraulic fluid, so the emergency backup is relative simple and easy.

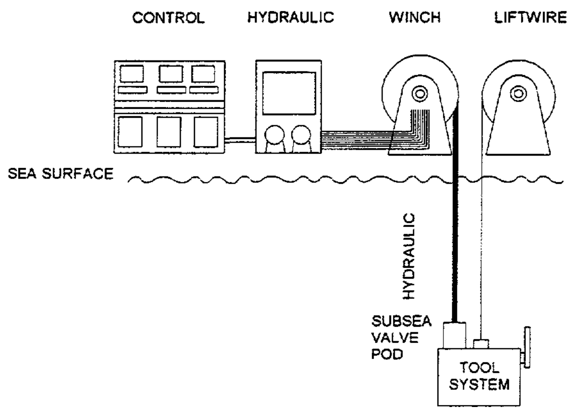


Figure 5.16 Direct hydraulic pilot operated valve pod

Table 5.32 Evaluation criteria for pilot hydraulic operated system

	Criteria	Scale (1 to 10)
1.	Reliability, System	8
2.	Reliability, Operation	7
3.	Reliability, Independence to other equipment	8
4.	Cost, Operation	6
5.	Control signal, Amount of	6
6.	Feedback, Amount of	2
7.	Cost, Maintenance	5
8.	Cost, Manufacturing	4
9.	Response time	6
10.	Energy consumption	4
11.	Flexibility to modification	3
12.	Complicity of system	5
13.	Space requirement	5
14.	Testability	3
	Total	63.9

Drawback for such a solution is also obvious. As we know, pure hydraulic system gives no feedback about the status of actuation system except pressure and flow in the hydraulic system. Many of the functions' operations are very much dependent on the tool operator's observation through ROV camera to obtain visual conformation of the status of system. Normally this is the only way to obtain such information. The tool operator must have very good coordination with ROV operator in order to obtain a satisfactory picture. Misunderstanding between operators and fatigue of operator may occur during a relative long time of concentration. High pressure loss, larger place occupied hydraulic umbilical; relative high risk to damage; complex operate procedure; long response time, expensive to manufacturer are among the disadvantage of this system. Too much wires and umbilical cause addition problem for equipment handling. Because the long delay time can cause the system into an unstable status, so it is not possible to be used working depth larger than 500 meters.

2. Directly operated and powered via ROV

Since some customer requires no electrical or electronic equipment subsea, and pilot hydraulic control system can not be used in larger water depth. So someone has developed one concept that control the tie-in system by ROV.

ROV operates the equipment directly through the ROV panel installed on the tool. The required control fluid is supplied by underwater matting stab (coupler). This alternative gives cheapest solution from the equipment cost, and has no electrical or electronic equipment underwater. Since all the operation is basic manual controlled by using of ROV manipulator, so the operation cost is increased dramatically because the long time needed to operator every single ROV valve. The most cost required for a separate control is eliminated because only ROV manipulator operator is required in the operation.

There are a few problems associated with this alternative since all the functions are manual controlled, there is no interlock or similar to prevent faulty operation. The high demands on the multi-roll operator causes one to tire quickly, that also increases the chance of malfunction. So this alternative gives the lowest operatability and the highest operation cost. The operating time by using the ROV manipulator will also dominate the operation time. This system is excellent to be used as a backup system for all the other system.

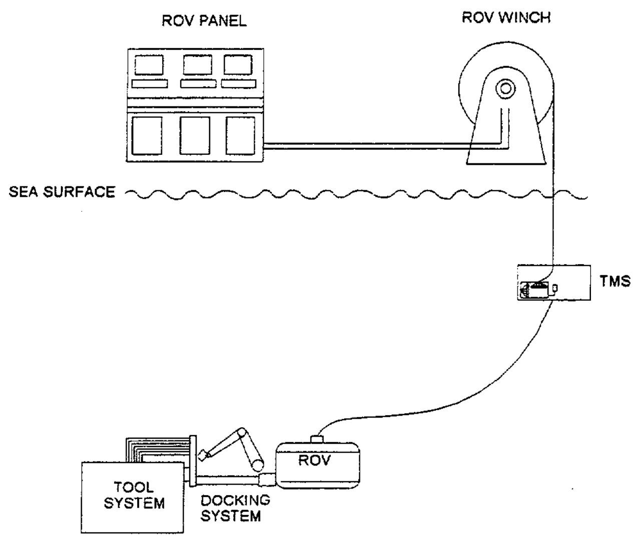


Figure 5.17 Directly operated and powered via ROV

Table 5.33 Evaluation criteria for ROV operated and powered system

	Criteria	Scale (1 to 10)
1.	Reliability, System	8
2.	Reliability, Operation	1
3.	Reliability, Independence to other equipment	1
4.	Cost, Operation	3
5.	Control signal, Amount of	6
6.	Feedback, Amount of	2
7.	Cost, Maintenance	6
8.	Cost, Manufacturing	8
9.	Response time	3
10.	Energy consumption	6
11.	Flexibility to modification	3
12.	Complicity of system	7
13.	Space requirement	10
14.	Testability	3
	Total	48.4

3. ROV powered subsea control system and valve pod

This alternative uses spare power and signal capacity in the ROV. Both spare hydraulic power and electrical from ROV can be used to drive HPU (Hydraulic power unit) on the ROV. The spare quad or fiber optic cable inside ROV umbilical is used to transfer control signal to the control system on the tool.

The ROV is acting as a tool and power/signal carrier. ROV is used for transport the tool from deployment equipment to working site. After pull-in preparation, the ROV will lock itself on top of the tool and stay there until the whole operation is accomplished.

This alternative gives fewer control/utility lines from surface. Since control signal is transferred in form of electricity, so faster response time and build-in feedback are possible to achieve. This alternative is using the existing ROV communication system. Only very few addition devices, such as control console and signal converter, are needed. Connection between ROV and tool is though a specially designed frame with locking device and power/communication interface. The frame is bolted on the ROV and cable/hoses are connected to juction box on ROV, so the modification of ROV is reduced to minimal, and therefore use ROV by chance is become a reality. The working depth for this alternative is as same as the ROV working depth.

Internal communication between ROV operator and tool operator is also improved, since they can be located in the same control room. The disadvantages for this alternative are that the requirement of underwater coupling of control fluid and/or electronic signal makes the connecting mechanism relative complex and easy to damage. This alternative also increased the dependency of ROV, and makes the already heavy loaded ROV loading even high therefor reduced the reliability of ROV. If anything goes wrong in ROV system, the tool system will be dead at same time. Since the working ROV is locked on the tool, so at least one more ROV is required for observation purpose. Another limitation is that since the tool system is deployed on assistance of ROV, so the weight and size of tool are limited. Tool designed for larger diameter pipe line is difficult to use.

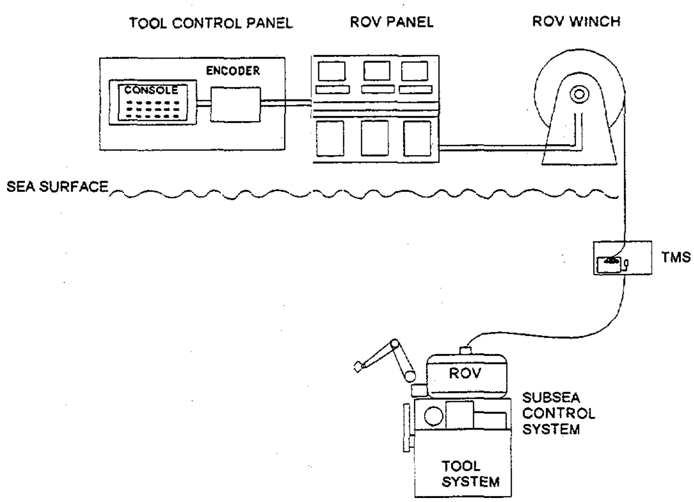


Figure 5.18 ROV powered subsea control system and valve pod

Table 5.34 Evaluation criteria for ROV powered subsea control system

	Criteria	Scale (1 to 10)
1.	Reliability, System	8
2.	Reliability, Operation	3
3.	Reliability, Independence to other equipment	9
4.	Cost, Operation	8
5.	Control signal, Amount of	9
6.	Feedback, Amount of	8
7.	Cost, Maintenance	6
8.	Cost, Manufacturing	7
9.	Response time	9
10.	Energy consumption	8
11.	Flexibility to modification	7
12.	Complicity of system	8
13.	Space requirement	8
14.	Testability	7
	Total	72.5

4. Subsea HPU and multiplexed control signal from surface

This alternative uses a combined lift and power/signal umbilical to deploy the tool. Dedicated surface control system and subsea control system are used to control the tool..

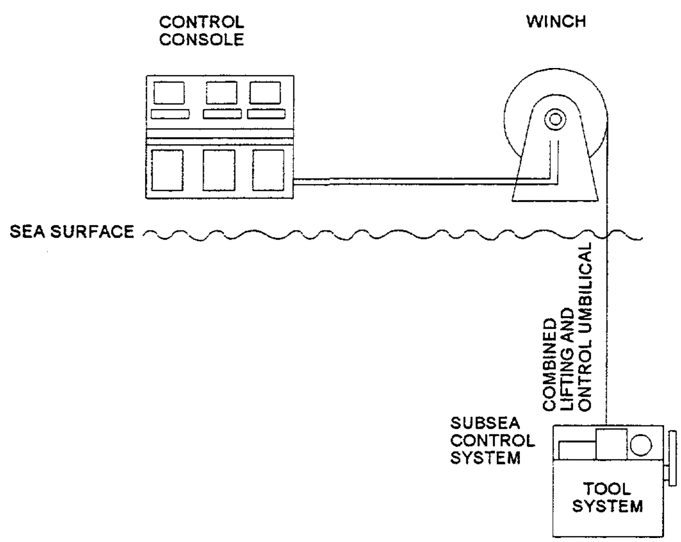


Figure 5.19 Subsea HPU and multiplexed control signal from surface

With implementation of electronics in the control system, the flexibility and signal channel of the control system increased dramatically (compare with pilot hydraulic operated system). Since feedback signal can be incorporated into control system, the monitoring condition is also improved very much. Water depth limitation is removed for most of the achievable water depth (1000 m and deeper). It can also remove the weight limitation on ROV assisted system. Best of all, it does not depend on the status of ROV anymore, so the reliability of the system is easier to guarantee.

Disadvantage: With the umbilical connected to the surface, the management of the umbilical is more complex. Heave compensated equipment has to be used, which is very expensive. The use of electronic devices demands a different kind of maintenance personnel, that may not available on board ship at that time.

Table 5.35 Evaluation criteria for surface powered subsea control system

	Criteria	Scale (1 to 10)
1.	Reliability, System	8
2.	Reliability, Operation	8
3.	Reliability, Independence to other equipment	9
4.	Cost, Operation	8
5.	Control signal, Amount of	9
6.	Feedback, Amount of	8
7.	Cost, Maintenance	6
8.	Cost, Manufacturing	4
9.	Response time	9
10.	Energy consumption	9
11.	Flexibility to modification	8
12.	Complicity of system	8
13.	Space requirement	6
14.	Testability	7
	Total	79.2

5. Subsea HPU and multiplexed control signal from ROV

We have discussed ROV assisted tool system that uses power system on the ROV and tool directly powered and controlled from surface. Both of them have their limitation and advantage. One possible solution can be a good compromise of both of them.

The configuration of this alternative is a combination of two of alternatives. The subsea control system and hydraulic power unit are the same as the one used for surface controlled system, and the surface control system is the same as ROV assisted system.

The power and signal are transferred through the ROV main umbilical to the TMS (Tether Management System). The power and control signal to tool control system are connected from junction box on TMS. Since the main umbilical has much more spare capacity for both power and signal than tether from TMS, therefor more feedback signals and power are possible to obtain. A small take up reel on the TMS can store the necessary length of tool control umbilical which is a small multi-core umbilical. An underwater matable multiple connector with locking device is used to transfer power and signal.

This alternative does not depend on system status of ROV. Even the ROV is broken down, as long as the ROV main umbilical is not cut, the tool system can work properly by using its own sensor and feedback information. To replace the failed ROV is also easier than ROV assisted system, since ROV itself is not locked with the tool, only the connection from one TMS needs to change to another one. One other good thing for this alternative is that the working ROV which is occupied all the time for the ROV assisted system is free to move, observation and doing necessary work without difficulties

Disadvantage: Besides the tool weight limitation, this alternative also causes a more complicated procedure of operating ROV, since there is one more umbilical around ROV working range. However, a non-moving umbilical should be better than another moving umbilical.

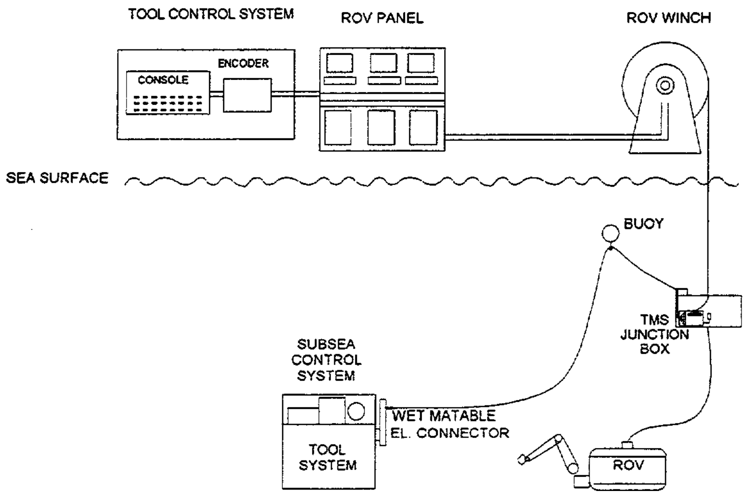


Figure 5.20 Subsea HPU and multiplexed control signal from ROV

Table 5.36 Evaluation criteria for Subsea HPU and multiplexed control signal from ROV

	Criteria	Scale (1 to 10)
1.	Reliability, System	8
2.	Reliability, Operation	8
3.	Reliability, Independence to other equipment	9
4.	Cost, Operation	8
5.	Control signal, Amount of	8
6.	Feedback, Amount of	6

	Criteria	Scale (1 to 10)
7.	Cost, Maintenance	7
8.	Cost, Manufacturing	9
9.	Response time	9
10.	Energy consumption	9
11.	Flexibility to modification	8
12.	Complicity of system	8
13.	Space requirement	8
14.	Testability	7
	Total	80.4

6. Summary of control system type evaluation

Based on the itemized evaluation, we can make a summary of the result to show how good a control system is.

The result shows that the best form of control system is the one with subsea HPU and controlled via ROV umbilical. The ROV direct operated alternative is most inappropriate to be used as primary control solution.

From Table 5.37, we can find that the direct hydraulic pilot operated system scores the fourth, the result is higher than the alternative -- directly operated and powered via ROV.

Table 5.37 Summary of control system type evaluation

Communication method	Result	Comment
Direct hydraulic pilot operated	63.9	High reliability, safe, medium depth, simple subsea slow response, little feedback, expensive surface equipment
Directly operated and powered via ROV	48.4	High reliability of subsea component, slow response, low operation reliability, highly skilled operator required, little feedback, complicated subsea procedure
ROV powered subsea control system	72.5	Large water depth, high reliability in equipment and operation, relative complicated operation, simple surface equipment
Subsea HPU and multiplexed control signal from surface	79.2	Large water depth, no limit on tool capacity, high reliability in equipment and operation, sufficient feedback, relative expensive surface equipment
Subsea HPU and multiplexed control signal from ROV	80.4	Large water depth, no limit on tool capacity, high reliability in equipment and operation, simple surface equipment

5.6.2 Functional evaluation

1. Normal operation function

The evaluation of PICT functions are summarized as follows:

Table 5.38 PICT Functions

Required basic function	Fulfill by PICT function
Able to keep tool at position	Tool Lock Down
Able to transfer pull force to the structure	Minipost on structure
Able to align termination	Funnel Hatch, Funnel Tilt, Center Box
Able to apply sufficient pull in force	Pull-In Winch
Able to bring to termination towards each other	Termination Stroke
Able to put the mechanical clamp on to the two termination hubs	Connector Elevator
Able to hold connector on tool	Connector Latch
Able to insert seal plate between two seal surface	Connector Built-in
Able to lock termination on place	Cramp Wedge and Cramp Bolts
Able to release pull head from termination	Pullhead Receiver
Able to offer sufficient pull in distance	Surface winch and Wire Feeder
Able to make tight contact between seal surface on two termination hubs	Connector Built-in nut tighten by Torque Tool
Able to carry out pressure test to verify the connection	Seal Test
Inspection and clearing termination surface	not built-in, but by special designed ROV tool

2. Accidental intervention

Hydraulic PICT ROV Intervention functions are listed in Table 5.39.

Table 5.39 ROV Hydraulic Intervention

Required backup function	Fulfilled by function
Free termination	Funnel Tilt
Free termination	Termination Stroke
Free connector	Connector Latch
Free termination	Funnel Lock
Maintain the termination at safe status	Termination Lock Wedge
Release pull-in wire	Pull-In Winch
Free connector	Torque Tool Break Out
Free connector	Torque Tool Engage Break Out
Free connector	Center Box Stroke

Some of the PICT functions also include mechanical ROV Intervention, they are listed in Table 5.40.

Table 5.40 Mechanical ROV intervention

Required backup function	Fulfilled by function
Free tool	Tool Lock down
Free connector	Connector Latch
Free pull-head	Pull head Release
Free connector	Torque Tool Engage Make Up
Free connector	Torque Tool Engage Break Out

3. Control Panel

Control Panel layout: All the function keys are grouped according to logic function groups. Every function key has corresponding label and logo for each action and ROV backup function.

The function group is classified by task requirement, group one is "Common Functions", group two is "Deployment & Pull In Mode" and group three is "Connection Mode".

Common Functions group includes functions that are common for both pull-in and connection operation, such as tool lock down, etc..

Deployment and Pull-in mode group includes functions related pull-in operation such as Pull-in winch, pullhead receiver function, etc..

Connection Mode group includes functions related to connection operation, such as connector elevator and torque tool, etc..

Switches for System Power and operation mode are used to select system mode and operation mode. Buttons and switches for console lamp test and speed control are also located on console panels.

Indication lamp and digital meter display of flow and pressure for hydraulic power unit are arranged in a way that is obvious for the operator to recognize. Audible alarms for reservoir level, low pressure and filter chock are also presented to get operator's attention. Table 5.41 lists available feedback information related to system status. With feedback information, the operator can have an overview of system status and mode of operation.

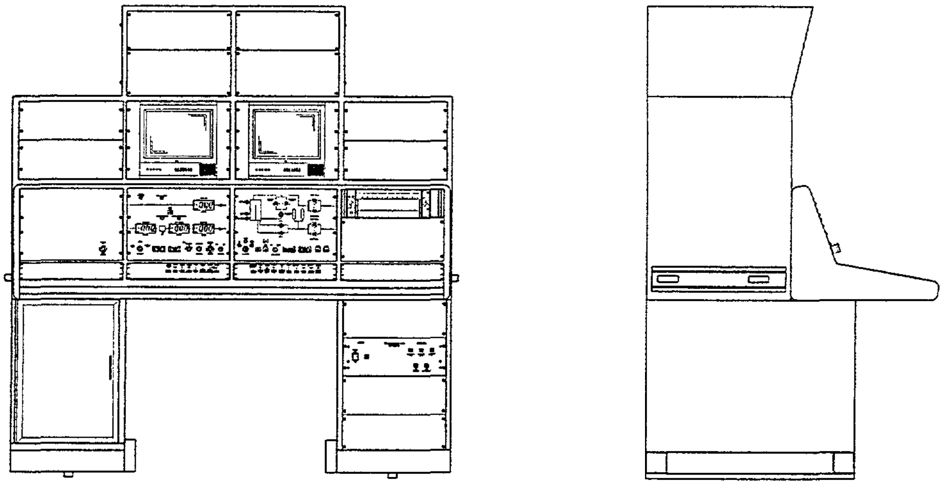


Figure 5.21 General arrangement of PICT control console

Table 5.41 Available feedback on control console and in control room

System variable	Information type	Acquisition method
Pressure of hydraulic system	Pressure	Pressure gauge/transducer
Reservoir level indication	Position	Level meter
High temperature	Temperature	Temperature transducer
Gas/Fire	Gas content	Gas sensor
Filter status	Pressure difference	Pressure transducer
System Flow	Flow	Flow meter
Pump pressure	Pressure	Pressure gauge/transducer
Interlock indication	Internal Flag	Internal status
Critical function indication	Internal Flag	Internal status
Mode indication	Internal Flag	Preset status

4. Operation procedure

Interlock indication between functions is designed into the control program, this reduces significantly the risk of mechanical damage. The design of control panel gives relatively good overview of system status. Mode indication and interlock indication can tell operator the status they are.

To activate a function is also intuitive. Operator can select a function first, then the lamp on the button is starting to flush. When the Execute and Function buttons are pushed, the lamp becomes constant light and corresponding function is activated. If the requested function is critical, then the critical lamp will flush. The operator needs to use two hand operations, first select Enabled and then Execute, then the critical function is activated.

The design of MQC plates makes the connection and disconnection of hydraulic lines fast and easier. Dummy control panel and testing hoses with adapter made function test easy and flexible.

With all the hydraulic components made in stainless steel, the risk of corrosion is also minimized.

5. Environment and safety

Water cool air condition is installed for maintain inner climate. Alarm, emergency exit, emergency power and light are available. Walkie-talkies are used for internal communication between different parts of system.

5.7 Conclusion and Recommendation for PICT

5.7.1 Conclusion of PICT control system

By comparing evaluation criteria in last sections, we know that the existing PICT (Pull-In and Connection Tool) can fulfill all the "Must" requirement for the task and from customer.

The whole control system design has considered operation, test, backup, but not training.

The system concept chose hydraulic pilot control from surface by the requirement from customer, "No electronic component subsea", so there are only hydraulic components located subsea. We have discussed some of the characteristics of this type of system and the way of communication. This alternative ranked fourth (Table 5.37) with 63.9, and we knew this alternative is not very good for gathering feedback information and built-in faulty checking.

From survey of operator, the operating experience obtained by operators shows that the tool functions as it should. High reliability of tool is maintained by function test and constant check and maintenance before and after each tie-in operation, the control system itself demands very little of maintenance.

My conclusion for PICT control system is that the design of system is very good on basis of the customer, but it is crippled by the fact that only hydraulic system can be used subsea. Some more feedback information is needed, and working environment design should consider more for different operator and space needed in operation. Fixed intercom will also improve the quality of internal communication and avoid the disturbance to control element (such as solenoids) caused by certain radio frequency.

5.7.2 Recommendation of PICT control system modification

From functional and ergonomic analysis we made from before, we also found there are places for improvement, if the pre-condition "No electronic subsea" can be changed.

1. Feedback information

Monitoring of many the function requires video picture supplied by ROV. Those pictures sometimes are not clear or stable enough to make good judgment. If some of the information can use simple and reliable sensors, the quality of feedback will be much better. The following tables are some of the signal I think is useful and modification needed on tool.

Table 5.42 Useful Feedback Signal type and measurement variable

Function	Measurement	Variable
Lock down	Position	Open Close
Pull-in Winch	Pressure/Position	Pressure/End points
Connector Latch	Position	Open/Close
Connector Elevator	Position	End points
Connector make up	Position	Number of Stroke

Table 5.43 Additional feedback on control console required

System variable	Information type	Acquisition method
Tool Lock down	Position	Position sensor
Pull-in Winch	Pressure/Position	Pressure transducer/Position sensor
Connector Latch	Position	Position sensor
Connector Elevator	Position	Position sensor
Connector make up	Position	Position sensor

Table 5.44 Modification in tool

Function	Sensor type	Signal Type
Tool Lock down	Inductive	Digital, On/Off
Pull-in Winch, Pull-in Force	Pressure transducer	Analog
Pull-in Winch	Inductive	Analog
Connector Latch	Inductive	Digital, On/Off
Connector Elevator	Inductive	Digital, On/Off
Connector make up	Inductive	Digital, On/Off

Table 5.45 Required Modification on control console

Function	Feedback type	Form of representation
Pull-in Winch, Pull-in Force	Visual	Digital counter
Pull-in Winch	Visual	Lamp
Connector Latch	Visual	Lamp
Connector Elevator	Visual	Lamp
Connector make up	Visual	Digital counter/Timer Converted distance

2. Space and working environment

On space and environment issues, the operators feelthat there is room for improvement. The following list is some recommendation for improvements inside control room.

Table 5.46 Space and working condition

Factor	Item of improvement
Chair	The Position/Height should be able to adjust for different operator size
Desk	The Size/Shape of control table should also consider the place for drinks and operation reference manual, since no online help is built-in
Light	The existing Color is not very good for long term concentration
Ventilation/Temperature	Since water source is not always available, so the air condition can not be used, force ventilation should also be consideration.

We found that he emergency exit could easily be blocked. A sliding door is recommended. Attention should be addressed to change the opening direction of the emergency exit from open towards outside to towards inside, or slide sideways.

6 Conclusions and future development

6.1 Design and evaluation method study

6.1.1 Conclusions

This design and evaluation method has been applied only to one example, namely the guideline based tie-in system, but the result shows that the method is valid. So we can say that the result of methodology research shows that it is possible to develop such a design and evaluation method as an assistance for developing of underwater control system. The author believes that a systematic approach for a control system development is the best way to develop a control system and often leads to a successful design.

During the development of the methods, many engineers showed their interest to have such a procedure to assist their work.

At this stage, the designer has to use the guide lines and techniques introduced in this thesis, manually develop the concepts and evaluate them. At later stage, the whole process will be based on relational database system, by inputting task and customer requirement, selecting different criteria from database to form final concepts. The result will consist a list of quantified scores, a report of advantages, disadvantages and recommendations. The method can be helpful to design a new product or improving an existing product. The time for a concept design will be dramatically reduced, and quality of concept will be guaranteed.

6.1.2 Recommendations for future work

To utilize this method to more general underwater control systems, more research should be carried out on bases of this work. We need to develop a database consists most if not all the functional requirement, evaluation criteria related to different sub-system and component for the underwater system we are going to work with.

The most important criterion for a satisfactory underwater system design is what the customer really wants. Understanding customer requirement itself is a very large and complicated tasks. Attention should be paid to the way of forming question and the coverage of questionnaire for customer survey.

Collecting reliability data for different parts of system is also crucial, since such data will be one of the most important criteria for evaluating a solution. For underwater systems, the lack of reliability data leads to under or over maintenance of the system, both of them may cause waste of operating time because of unexpected breakdown and unnecessary maintenance time.

Development of evaluation criteria is a special and important subject. The researcher should cooperate closely with user and designer to obtain the attributes related information for different sub-systems and components from their technical characteristics and application area.

When one study the underwater control system dynamic, the operator should always be considered as part of control loop. At this moment, most of the current study is based on aerospace control research, and many researchs have been based on studies of different estimators. Estimator algorithms used for underwater system's operator have not been developed much, since the perception characteristics are different from aerospace. Not many studies have considered that the operator for underwater equipment has to respond to basis of image presented on the screen and not in real life. Studies about how to give operator a more accurate and efficient way to recognize the working object should be carried out.

The possible future work can be arranged after the task sequence as listed in section 6.1.3.

6.1.3 Possible future work

1. In depth customer requirement survey
2. Build-up database for functions required for different tasks
3. New weighing factor method development
4. Develop a log book for operator register events during operation
5. Develop criteria for different components (sub-systems)
6. Reliability of parts involved in underwater system
7. Research on arrangement of control room for best ergonomic operation
8. Information, model based operation, environment model
9. Modeling of operator for underwater tasks
10. Autonomous control with supervisory control

6.2 Interesting topics in underwater technology development

Underwater technology is developing rapidly. Many topics are very interesting in relation to underwater working system.

6.2.1 Communication

1. Telemetry/Communication requirements
2. Video transfer
3. Design ROV compatible electro-optical connectors for data retrieval and power supply to the packages.
4. Long cable and the interconnections
5. Navigation, communication, and control of multiple vehicles
6. Multiple sensor packages and management of data for mission control and tactical database construction
7. Long-range acoustic transmission
8. Laser imaging enhancement transmission

6.2.2 Navigation/Sensor/Sampling/Tooling

1. Remote vehicle tooling development for scientific sampling
2. Telepresent control systems for ROVs

3. Added difficulties of sensing underwater (vs. terrestrial)
4. Task/terrain relative navigation and position
5. Manipulators for very deep applications > 4000 m

6.2.3 Energy

1. Reliable, cheap, high-density and environmentally friendly energy systems
2. Long-range power transmission

6.2.4 Control

1. Simulation and control of high-speed manipulation
2. Fine and delicate control
3. Motion Control
4. Inter-operability of underwater robotic vehicle systems
5. Intelligent distributed control
6. Realistic task-driven, high-level/low-level control and mission planning intervention

6.2.5 Training environment

1. Visual environments for training and control
2. Low cost simulators for reserve personnel

6.2.6 Other

1. Current application to date-remote inspection of nuclear facility containment vessels, hazardous waste disposal sites, storage tanks, ship wrecks and hydro-electric dam facilities, etc.
2. Creating standards for ROV used for inspection of hazardous environment including nuclear reactor and fuel reactors; and ROVs used in conjunction with divers for scientific exploration

Appendix

A.1 Other simple methods of evaluation between alternatives

1. Alternative versus Standard: Comparison across Attributes

This method takes the following two forms:

1) Disjunctive resolution. An alternative will be retained (not eliminated) if it meets the standard for at least one attribute.
2) Feasible ranges (satisfying). In this method an alternative is judged to be feasible only if it meets the standards established for all attributes

Example 1: For the problem in Table 4.1 (and using the standards in the right-hand column), set up a table (Table A.1) that indicates which alternatives do not meet the standard for which attributes. Then conclude which alternatives would be recommended with each of these methods: (a) disjunctive resolution and (b) feasible ranges.

Table A.1 Alternative versus standard

Attribute	X for Alternatives Not Meeting Standard			
	1	2	3	4
A				X
B			X	
C				
D		X	X	X

Result

(a) All alternatives meet the standard for at least one attribute.
(b) Only alternative 1 meets the standard for all attributes.

2. Alternative versus Alternative: Comparison across Attributes

This method is normally called a "dominance" check. If one alternative is better than or equal to some other alternative with respect to all attributes, and better for at least one attribute, the other alternative is said to be dominated and can be eliminated.

Example 2 For the problem in Table 4.1 comparison of all pairs of alternatives across all attributes will reveal that alternative 2 dominates alternative 3. That is, alternative 2 > alternative 3 (read as alternative 2 is preferred to alternative 3)

because, in the given attribute order,

90 > 80; good > poor; 38 > 35; and 6 > 5.

Further inspection will find no alternative that is dominated.

3. Alternative versus Alternative: Comparison across Alternatives

This method is of two types:

1. Lexicography. This involves first ranking attributes by importance. For the most important attribute, choose the alternative, if any, which is best. If there is a tie between two or more alternatives, one should go to the second most important attribute and choose which of those "remaining" alternatives, if any, is best. This process continues in this way until a single alternative emerges, or until all criteria have been examined.
2. Elimination by aspects. This is like lexicography because it examines one attribute at a time, making comparisons among alternatives. However, it eliminates alternatives that do not satisfy the standard (minimum acceptable for that attribute) and continues until all alternatives exception have been eliminated, or until all attributes have been examined.

Example 3. For the problem in Table 4.1 assume that attribute importance rank are A > B> C> D and determine what alternatives remain alter applying (a) lexicography and (b) elimination by aspects, using the "standards" given in the right-hand side of the table. (A >B means that A is preferred to B, etc.)

Result (Table A.2)

a) For attribute A, alternative 2 is best and would be the choice.
b) Refer to the table in the solution for Table A.1.
c) Thus alternative 1 is the only survivor.

Table A.2 Alternative versus Alternative

Attribute	Alternatives Eliminated	Alternatives Left
A(most imp.)	4	1,2,3
B	3	1,2
C	None	1,2
D	2	1

Any of these methods can be tempered/altered with good judgment regarding the decision-making circumstances. In most cases it makes sense to allow what might be called "hands of imperfect discrimination" so that one alternative is not judged better than another just because it has a slightly higher value for one attribute when using "lexicography," or the other alternative just barely falls below one standard when using "elimination by aspects."

Table A.3 Example with four alternatives and five attributes

Attribute	Alternatives			
	P-1	P-2	P-3	P-4
A. Machine performance	Average	Above average	Average	Below average
B. Cost	350kNOK	300kNOK	280kNok	380kNOK
C. Serviceability	< 1 hr	1 - 1½ hr	1 - 1½ hr	1½ - 2 hr
D. Management/engineering effort	500 hr	700 hr	1100 hr	700 hr
E. Risk, lack of	Above average	Average	Below average	Average

4. Ranking of attributes (or alternatives)

Before attributes are weighted (or alternatives are evaluated), it is often desired to rank them in order of decreasing preference. This might be done by presenting the decision maker with a list of attributes (or alternatives) and asking him or her to rank them in order of preference. There is, however, a procedure that may make this task easier and provides a check on the internal consistency of the value judgments obtained. This is called the method of paired comparisons and is illustrated in the following discussion

Consider the five criteria (attributes) in Table A.3, which we now want to rank order. They are designated as follows:

A. Machine Performance
B. Cost.
C. Serviceability.
D. Management/engineering effort.
E. Risk, lack of

The method of paired comparisons submits attributes to the decision maker two at a time for preference judgments. In general, if there are N factors, $N(N - 1)2$ pairs must be judged. Assume that the results of this process are indicated by the following list of preference statements (as usual, the symbol > means "is preferred to" and = means "is equal to").

1.	A<B	6.	B>D
2.	A>C	7.	B>E
3.	A>D	8.	C>D
4.	A>E	9.	C=E
5.	B>C	10.	D<E

Table A.4 Preference Comparisons

	A	B	C	D	E	Number of Times Preferred
A	-		P	P	P	3
B	P	-	P	P	P	4
C			-	P	=	1½
D				-		0
E			=	P	-	1½

A good way to depict the pairwise comparisons and then determine rankings is shown by the matrix in Table A.4. In that matrix P is shown for each pair in which the row factor is preferred to the column factor. Note that the diagonal of the matrix is empty (since a given factor cannot be preferred to itself). A good way to make sure that all pairs of factors have been considered is to recognize that there should be a P either above or below the diagonal for all pairs, or in case of equal preferences, an = is shown both above and below the diagonal. Note that on the right-hand side of the matrix is shown the number of times the factor in each row is preferred. Thus, for this example, it is found that the rank order of criteria is B > A > C = E > D.

The foregoing scheme of deducing rankings assumes transitivity of preferences. That is, if A > C and B > A, then B must be > C. If the number of times a given factor is preferred to another is equal for two or more factors (except in the case of ties), there is evidence of lack of consistency (i.e., intransitivity), which suggests the need for questioning preference judgments for the criteria involved.

A.2 Calculation sheets

In order to calculate the evaluation scores, a workbook is made. This workbook is based on Microsoft Excel, and consists three worksheets: Input sheet, Weighing factors and Result sheet. The following are two examples of calculation.

A.2.1 Calculation sheets for evaluating communication methods

Input sheet for underwater communication systems

Critera		Alternatives				
		A	B	C	D	E
1	Cost, Manufacture	9	9	6	7	
2	Cost, Initial setup	9	2	10	10	
3	Depth, Operation	2	10	5	7	
4	Reliability, Operation	5	6	9	10	
5	Space requirement	9	8	2	8	
6	Communication, bandwidth	8	7	3	10	
7	Range, Operation	10	8	5	4	
8	Faulty detection	6	6	4	10	
9	Repair and replacement	8	2	5	8	
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						

Alternatives

A Radio frequency

B Acoustic

C Hydraulic umbilical

D Electric/Optic umbilical

E

Weighing factors for underwater communication systems

	Critera	Alternatives				
			Rank sum		Rank Reciprocal	
		Uniform	B	C	D	E
1	Cost, Manufacture	1	9	20	1.00	35
2	Cost, Initial setup	2	8	18	0.50	18
3	Depth, Operation	3	7	16	0.33	12
4	Reliability, Operation	4	6	13	0.25	9
5	Space requirement	5	5	11	0.20	7
6	Communication, bandwidth	6	4	9	0.17	6
7	Range, Operation	7	3	7	0.14	5
8	Faulty detection	8	2	4	0.13	4
9	Repair and replacement	9	1	2	0.11	4
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
	Total:	45	45	100	2.83	100

Result for underwater communication systems

Critera		Normalized weights	Alternative A		Alternative B		Alternative C		Alternative D		Alternative E	
1	Cost, Manufacture	35	9	31.8	9	31.8	6	21.2	7	24.7		
2	Cost, Initial setup	18	9	15.9	2	3.5	10	17.7	10	17.7		
3	Depth, Operation	12	2	2.4	10	11.8	5	5.9	7	8.2		
4	Reliability, Operation	9	5	4.4	6	5.3	9	8.0	10	8.8		
5	Space requirement	7	9	6.4	8	5.7	2	1.4	8	5.7		
6	Communication, bandwidth	6	8	4.7	7	4.1	3	1.8	10	5.9		
7	Range, Operation	5	10	5.0	8	4.0	5	2.5	4	2.0		
8	Faulty detection	4	6	2.7	6	2.7	4	1.8	10	4.4		
9	Repair and replacement	4	8	3.1	2	0.8	5	2.0	8	3.1		
10												
11												
12												
13												
14												
15												
16												
17												
18												
19												
20												
	Total:	100		76.4		69.7		62.2		80.6		

A.2.2 Calculation sheets for evaluating underwater control system types

Input sheet of underwater control system types

	Critera	A	B	C	D	E
		Alternatives				
1	Reliability, System	8	8	8	8	8
2	Reliability, Independency to other equipment	7	1	3	8	8
3	Reliability, Operating	8	1	9	9	9
4	Cost, Operation	6	3	8	8	8
5	Control signal, Amount of	6	6	9	9	9
6	Feedback, Amount of	2	2	8	8	8
7	Cost, Maintenance	5	6	6	6	6
8	Cost, Manufacturing	4	8	7	4	7
9	Response time	6	3	9	9	9
10	Enengy consumption	4	6	8	9	9
11	Flexibility to modification	3	3	7	8	8
12	Complicity of system	5	7	8	8	8
13	Space requirement	5	10	8	6	8
14	Testability	3	3	7	7	7
15						
16						
17						
18						
19						
20						

Alternatives

- A Pilot Hydraulic operated system
- B ROV operated and powered system
- C ROV powered subsea control system
- D Surface powered subsea control system
- E Subsea HPU and signal from ROV

Weighing factors of underwater control system types

Critera		Alternatives				
			Rank sum		Rank Reciprocal	
		Uniform	B	C	D	E
1	Reliability, System	1	14	13	1.00	31
2	Reliability, Independency to other equipment	2	13	12	0.50	15
3	Reliability, Operating	3	12	11	0.33	10
4	Cost, Operation	4	11	10	0.25	8
5	Control signal, Amount of	5	10	10	0.20	6
6	Feedback, Amount of	6	9	9	0.17	5
7	Cost, Maintenance	7	8	8	0.14	4
8	Cost, Manufacturing	8	7	7	0.13	4
9	Response time	9	6	6	0.11	3
10	Enengy consumption	10	5	5	0.10	3
11	Flexibility to modification	11	4	4	0.09	3
12	Complicity of system	12	3	3	0.08	3
13	Space requirement	13	2	2	0.08	2
14	Testability	14	1	1	0.07	2
15						
16						
17						
18						
19						
20						
	Total:	105	105	100	3.25	100

Result of underwater control system types

	Critera	Normalized weights	Alternative A		Alternative B		Alternative C		Alternative D		Alternative E	
1	Reliability, System	31	8	24.6	8	24.6	8	24.6	8	24.6	8	24.6
2	Reliability, Independency to other equipment	15	7	10.8	1	1.5	3	4.6	8	12.3	8	12.3
3	Reliability, Operating	10	8	8.2	1	1.0	9	9.2	9	9.2	9	9.2
4	Cost, Operation	8	6	4.6	3	2.3	8	6.2	8	6.2	8	6.2
5	Control signal, Amount of	6	6	3.7	6	3.7	9	5.5	9	5.5	8	4.9
6	Feedback, Amount of	5	2	1.0	2	1.0	8	4.1	8	4.1	6	3.1
7	Cost, Maintenance	4	5	2.2	6	2.6	6	2.6	6	2.6	7	3.1
8	Cost, Manufacturing	4	4	1.5	8	3.1	7	2.7	4	1.5	9	3.5
9	Response time	3	6	2.1	3	1.0	9	3.1	9	3.1	9	3.1
10	Enengy consumption	3	4	1.2	6	1.8	8	2.5	9	2.8	9	2.8
11	Flexibility to modification	3	3	0.8	3	0.8	7	2.0	8	2.2	8	2.2
12	Complicity of system	3	5	1.3	7	1.8	8	2.1	8	2.1	8	2.1
13	Space requirement	2	5	1.2	10	2.4	8	1.9	6	1.4	8	1.9
14	Testability	2	3	0.7	3	0.7	7	1.5	7	1.5	7	1.5
15												
16												
17												
18												
19												
20												
	Total:	100		63.9		48.4		72.5		79.2		80.4

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