*Proc. Int. Symposium Teleoperation and Control*, 277-290
July 1988, © IFS Ltd and authors, ISBN 1-85423-009-3

# Development of a general purpose hand controller for advanced teleoperation

**K V Siva, A A Dumbreck, P J Fischer and E Abel**
**Harwell Laboratory, UK**

## ABSTRACT

A development project has been initiated at Harwell Laboratory to investigate the feasibility and ramifications of a general purpose hand controller for bilateral control of standard 6-axis manipulators and robots. By general purpose, it is meant that the input command device shall be capable of co-ordinating and controlling the remote manipulator's joints as the operator desires. Forces and torques may also be reflected on the three positional and three orientational axes of the hand controller giving the operator a kinesthetic sense of the task he is manipulating remotely. Since the kinematics and dynamics are dissimilar between the hand controller and the manipulator, the implementation of the unilateral and bilateral control system requires a computer to deal with these disparities. This paper reviews the state of the art of general purpose hand controllers and examines the use of parallel link and hybrid serial-parallel link structures for use in the development of an efficient bilateral hand controller, as part of the on-going Nuclear Robotics Programme at Harwell.

## 1. Introduction

The increased need for remote manipulation in hazardous environments - Nuclear, Undersea, Outerspace etc, has been widely recognized. Complex and unplanned tasks are difficult to perform with programmable or robotic remote manipulators. Human judgement, skill and sensory interaction are often needed to perform these tasks successfully and safely. The sensory information to the operator during remote manipulation includes vision, hearing and kinesthetic sensations. Additional information on the remote task environment (such as temperature, humidity etc) is also beneficial in these operations. A mechanical input device such as a joystick or a master arm is normally used to control the movements of the remote manipulator. Force reflection is added to the input device to enhance the remote manipulative performance. The state of the art of advanced general purpose hand controllers is not well developed. Perhaps an evidence for this is the number of different input devices used today to control robots and manipulators. The comparative merits are not yet established. This paper describes the features of a compact 6-axis input device based on parallel linkages for single-handed operation of a remote manipulator, currently under development at Harwell Laboratory.

Even though the emphasis made in this paper is the use of a general purpose hand controller in the control of a general 6-axis "shoulder-elbow-wrist" type of manipulator, it has potential for uses in a large variety of manipulations. The basic requirements for such a device are examined from the viewpoint of general manipulations and efficient operator interactions. These basic requirements for a good general purpose hand controller are believed to be:

(i) The controller must have six degrees-of-freedom so that the 6-axis slave manipulator can be commanded by displacements in the controller to move the slave to any point in its workspace and be orientated at any desired attitude angle.

(ii) The control input device must be easily backdriveable so that the fatigue levels of the operator can be kept to a minimum.

(iii) The operator must be capable of generating input commands of more than one axis simultaneously with minimum or no unintended movements on other axes using one hand only.

(iv) It must be possible to indicate the external forces/torques being applied at the slave manipulator, during manipulation, to the operator using force/torque feedback to the hand controller.

(v) A suitable base in the hand controller for the operator to rest his wrist so that fine motions can be generated when needed in performing a remote task.

An example of a control input device embodying most of these basic requirements is the bilateral or force-reflecting master-slave manipulator. The disadvantages of this device are its large operational volume, thus increasing fatigue and lessening safety, and its high cost. It is mainly under these circumstances, that a general purpose efficient hand controller becomes attractive.

## 2. Review of General Purpose Hand Controllers

The range of general purpose hand controllers can be classified into two broad categories:

(i) Geometrically dissimilar master arm
(ii) Cartesian co-ordinate command input device

A geometrically dissimilar compact master arm was developed by JPL Teleoperator Laboratory (1),(2),(3) and is called a Universal Force Reflecting Hand Controller. Fig 1 shows the kinematic arrangement of this device. It has been mechanically and electrically counterbalanced and provides force reflection.

There are several types of cartesian input devices developed for the control of a 6-axis manipulator in the cartesian frame. Fig 2 shows the X-Y-Z motion generation by the controller developed at MIT's Man-Machine System Laboratory (4). A special purpose joystick handle with micro switches is used to command the other axes of motion. An experimental 3-D joystick developed by CEGB's Marchwood Engineering Laboratory (5) also uses the pure X-Y-Z form of kinematics. Fig 3 shows a hand controller with X-Y-Z translational motions and usual pitch/roll motions developed by Harwell Laboratory specifically for the control of a micro manipulator called Elite. The hand controller under development by the University of Florida is shown in Fig 4 (6), and is called a Universal Floating-Hand Controller. The device does not provide force reflection at present (7).

The 6-axis control input device developed by CAE Electronics Ltd, Canada (8) provides ± 0.5ins (13mm) for the X-Y-Z motions and ± 15 degrees for the rotary $\alpha$-$\beta$-$\gamma$ command inputs. An ordinary 3-axis joystick is used for the rotary motions. The X-Y motions are generated using a parallelogram. linkage arrangement and the Z-movement by a normal translational action. All the axis of movements are sprung to return to the neutral position and no other external force feedback is provided.

The input devices described above require some displacement to generate either position or rate command(s). However, it is also possible to generate cartesian frame based input commands without any displacements using a fixed force/torque ball, Fig 5. It would not be possible to use bilateral control to provide force reflection using these devices. A number of controllers are commercially available based on Force/Torque Ball Joysticks (9),(10),(11). Sometimes two 3-axis joysticks are used to generate X-Y-Z motions and wrist orientations but they limit the use of single-handed operation (12),(13), Fig 6.

It must be pointed out that there is no hand controller which could even approximately match the dexterity and manipulative capabilities of the human hand. Two critical performance parameters, the task performance time and the number of errors made during the performance of the task can provide a good index for the effectiveness of a hand controller. This could be compared against the performance when the task is carried out directly by a human operator.

## 3. The Principle of Single-Handed Operation

Amongst the possible methods and devices for controlling a remote manipulator, identical master-slave control system with force reflection nearly approaches the direct operations by an operator. However, it limits the human capabilities - necessitates the use of the other hand to control interaction of axes, increases operator fatigue and imposes safety problems under bilateral control. It will also be difficult to control other functions in the system such as remote viewing when both hands are needed for the control of manipulation. Sometimes, two manipulator arms are used to perform a task. For example, one arm holding an object while the other is used to do some work on it, or use of both arms to move an object in a desired path or trajectory. Therefore, what is needed in these instances, is a single hand controller to control the movements of an operator. The input device must ideally permit an operator to direct each of the two arms to grasp an object at chosen locations, simultaneously if necessary and then to perform a desired operation such as moving it from one place to another along a designated path.

Computer control can be used to adopt strategies that will minimise operator fatigue and maximise the system performance. In the bilateral control mode, forces due to the dead weight of the slave manipulator, can be cancelled out and force-feedback actuation can be turned off when the manipulator is stationary. Different control modes such as position control, rate control, force control and bilateral control can be selected at will to accomplish a task. To make the best use of human judgement, all possible information on task environment and the task itself must be communicated to the operator for interpretation or perception.

It will be useful to have a larger displacement range in the hand controller as practicably as possible to enhance the operator's accuracy. Since there is disparity between the motion ranges in a compact hand controller and a slave manipulator, it is necessary to incorporate different control modes. The motion ranges could be scaled to match each other under position control. Alternatively, rate control can be used for the gross motions in the workspace and 1:1 fine incremental motions between the hand controller and the slave unit near the task zone. Should the hand controller reach one or more of its displacement travel limits, it could be allowed to return to the neutral position under computer control without causing any movements in the slave, (similar to the positioning of the cursor in a display screen using a mouse). Almost all researchers now agree that an efficient hand controller must be capable of providing force feedback to the operator. Kinesthetic sensations can be regarded as essential in certain kinds of remote manipulation because most actions depend upon the perception of the manipulative forces. In addition to the enhancement of operator's commanding accuracy, larger motion ranges in the hand controller are also essential to allow the force feedback actuators sufficient displacement for better functioning.

The important principles need to be embodied in the design of a general purpose hand controller for single handed operations can therefore be summarised as follows:

- (a) Compact kinematics or geometry
- (b) Sufficient displacement ranges
- (c) Easy backdriveability and minimum cross coupling between motions
- (d) Kinematics solvability for computer-aided control
- (e) Mechanism rigidity for achieving increased servo stiffness in the force feedback servos.

The need for the solution of the direct kinematics problem can be easily understood when the parallel link mechanism is used as an input device, Fig 7. The inverse kinematic problem and the Jacobian matrix of the mechanism are needed when adding force reflecting characteristics to this input device, Fig 8.

It is also being considered whether a hybrid form of the mechanism, using part of the parallel link topology for the X-Y-Z motions and the conventional serial link arrangement for the wrist $\alpha$-$\beta$-$\gamma$- motions (as used in the earlier Harwell's hand controller for the Elite manipulator) could also be a good compromise between computational complexity and mechanical simplicity.

## 4. Description of the New Hand Controller

A new hand controller based on parallel linkage topology is under development at Harwell Laboratory, Fig 9. Some research has already been carried out on the use of parallel links for stiff robotic structures after Stewart and McGough (14) who used this arrangement for the first time to generate aircraft flight simulations and tyre testing machine motions respectively. There are research machines based on this mechanism at the Marconi Research Centre (UK), University of Florida (USA), Oregan State University (USA), Massachusetts Institute of Technology (USA) and the National Research Institute for Information and Automation (INRIA - France). A commercial robot marketed by GEC, called "GADFLY" for the assembly of components in the electronics industry uses part of this topology (15). Three parallel links are used for the positioning and a serially linked conventional 3-axis wrist used for orientations. The mechanical arrangement using parallel compliant links has also been used to provide passive compliance in the end-effector for performing robotic assembly tasks (16). An experimental application has been reported where the robot performs an assembly task on a six degrees-of-freedom workstation based on parallel link mechanism (17). Some 6-axis force/torque sensors are also constructed around this parallel link structure (18).

The parallel mechanism is more rigid and more accurate than a serial mechanism but the disadvantages are more joints and smaller working volume. The joints in the parallel manipulator are passive and only the linear travels are active under computer control.

There are several forms of this 6-axis parallel mechanism being studied for various applications. Many authors have published material on the kinematic analysis of these mechanisms for use as a robotic device (19),(20),(21),(22) which indicates recent increased interest in this mechanism. As a robotic device, the kinematic problem is, as usual, "What are the values of joint (leg lengths) variables for a given position and orientation of the gripper in space?" However, as an input device or a hand controller, it is necessary to determine the cartesian position and orientation for a given configuration or leg lengths of the parallel link platform. Even though the values of the joint variables (ball joints, universal joints) are not needed in the control or use of it as an input device, the range of these joint variables is needed, for instance, during the design of the mechanism. E F Fichter et al has described a method for determining these values (23).

The displacement equations given in the Appendix show that the inverse kinematic problem of finding the leg lengths for a given end-effector position is readily solvable, but the direct kinematics problem is a rather difficult task since it involves the solution of a set of highly non-linear simultaneous equations. The situation is, therefore, exactly the opposite of the case of the kinematics of a serial link or open chain manipulator.

The hand controller is based on the conventional design of a parallel link manipulator. There is a Hooke or Universal joint at the base end and a large angle (25° - 40°) ball and socket joint at the platform end of the link. A backdriveable linear slide is interposed between these joints for the telescopic action of the links. This will be replaced by a backdriveable linear actuator (eg rack and pinion) when force feedback is to be added to the hand controller.

## 5. Conclusions

A feasibility study of a platform type of input device for remote manipulations has been carried out using mock-up models and elementary theoretical analysis. Findings until now show that a careful assessment is needed to determine a choice between a fully parallel link mechanism and a hybrid serial-parallel mechanism for use as a general purpose hand controller structure. It is believed that teleoperations can be efficiently performed using this type of compact displacement type of input device. It has features such as structural rigidity, a base for resting operator's wrist/hand and small but safe operational volume for bilateral control.

The input device presented in this paper will form one of the type of input devices available at Harwell in the future to make an assessment of Man-Machine Interface for motions between human operator and a remote manipulator or a robot. The types of input devices planned for this experimental assessment programme include the following:

(a) Scaled replica master arm (with and without force reflection)
(b) Two 3-axis joysticks (resolved cartesian rate control)
(c) Single fixed displacement 6-axis force/torque joystick
(d) Single displaceable 6-axis joystick (with and without force reflection)

The material presented in this paper will be experimentally evaluated, clarified and expanded in the future.

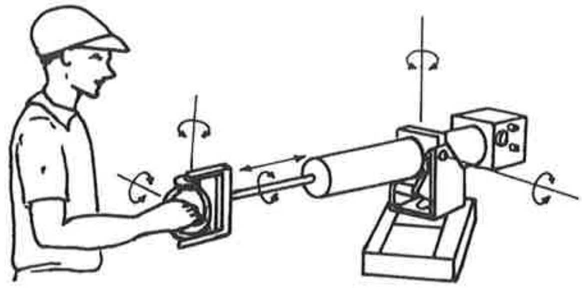


Fig. 1. JPL's Universal Hand Controller

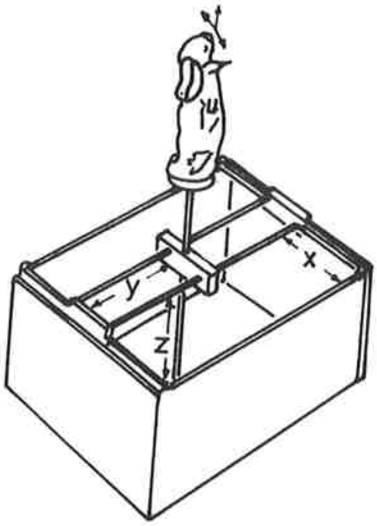



Fig.2. MIT's Hand Controller

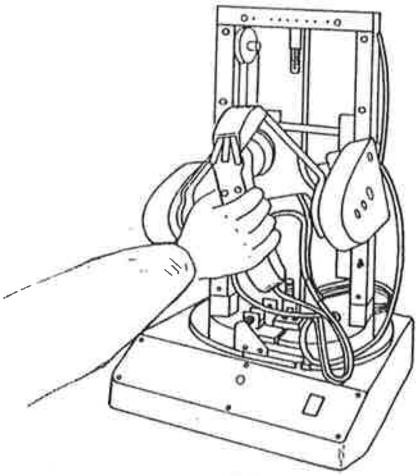


Fig.3. Harwell's Elite Manipulator Hand Controller

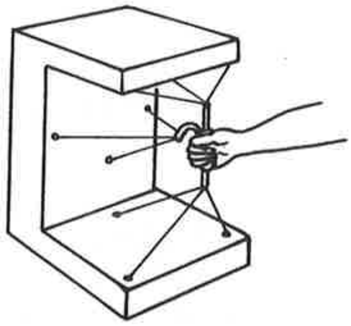


Fig.4. UOF's Hand Controller

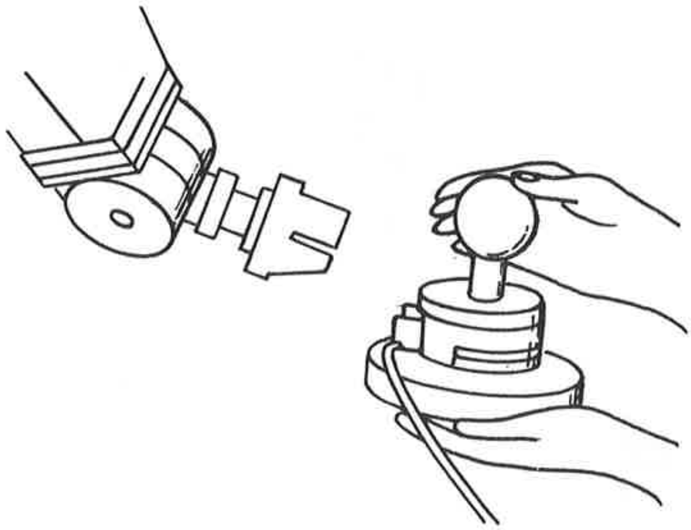


Fig.5 Force/Torque Ball Joystick

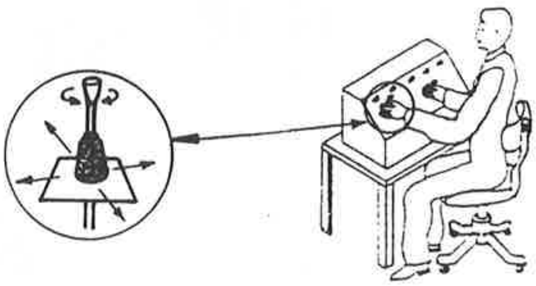


Fig.6 Use of Two 3-Axis Joysticks

JPL - Jet Propulsion Laboratory, University of California, USA
MIT - Massachusets Institute of Technology, USA
UOF - University of Florida, USA

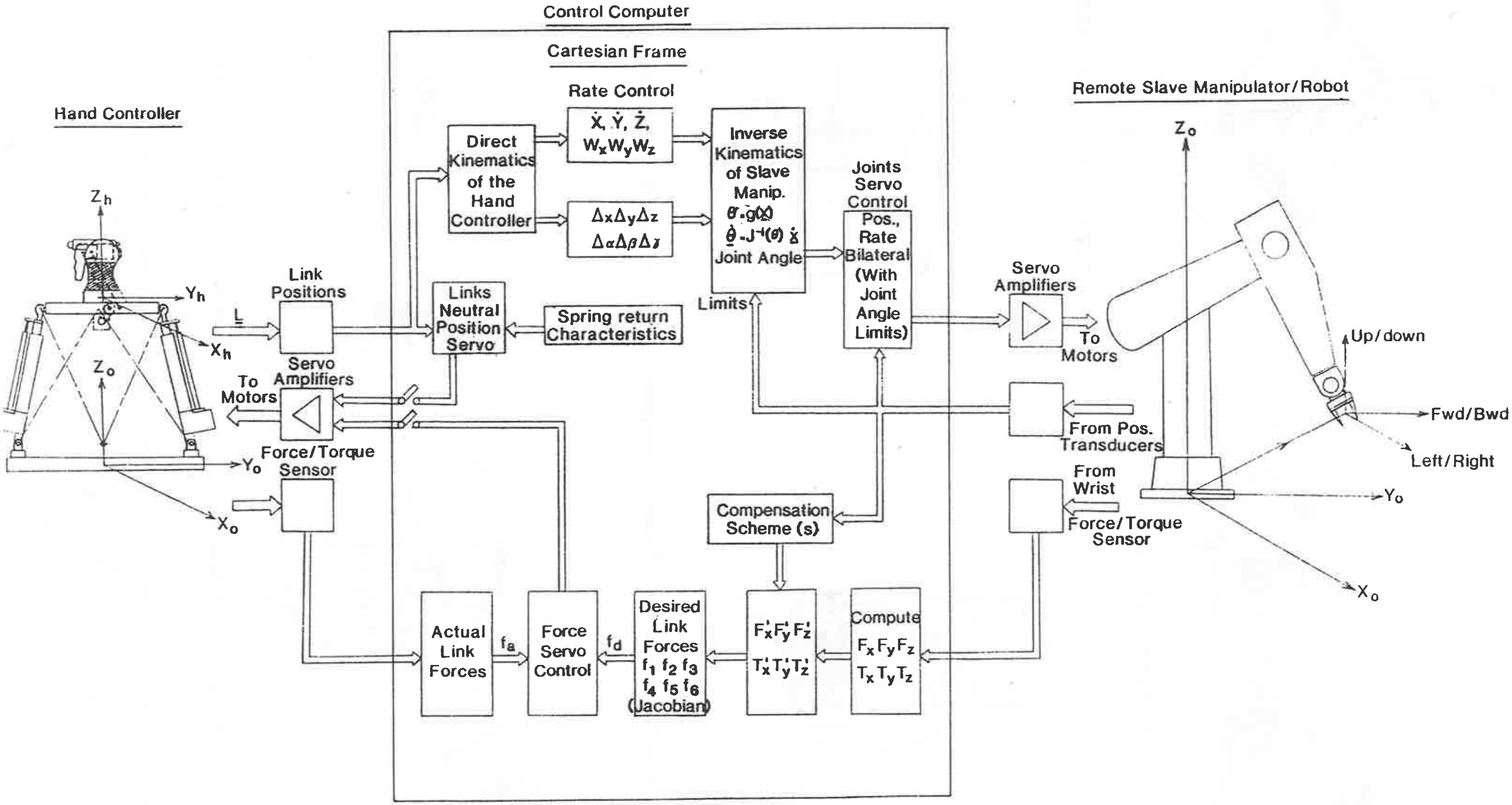



Fig.8 Bilateral Control of the Remote Manipulator Using the Parallel Link Hand Controller

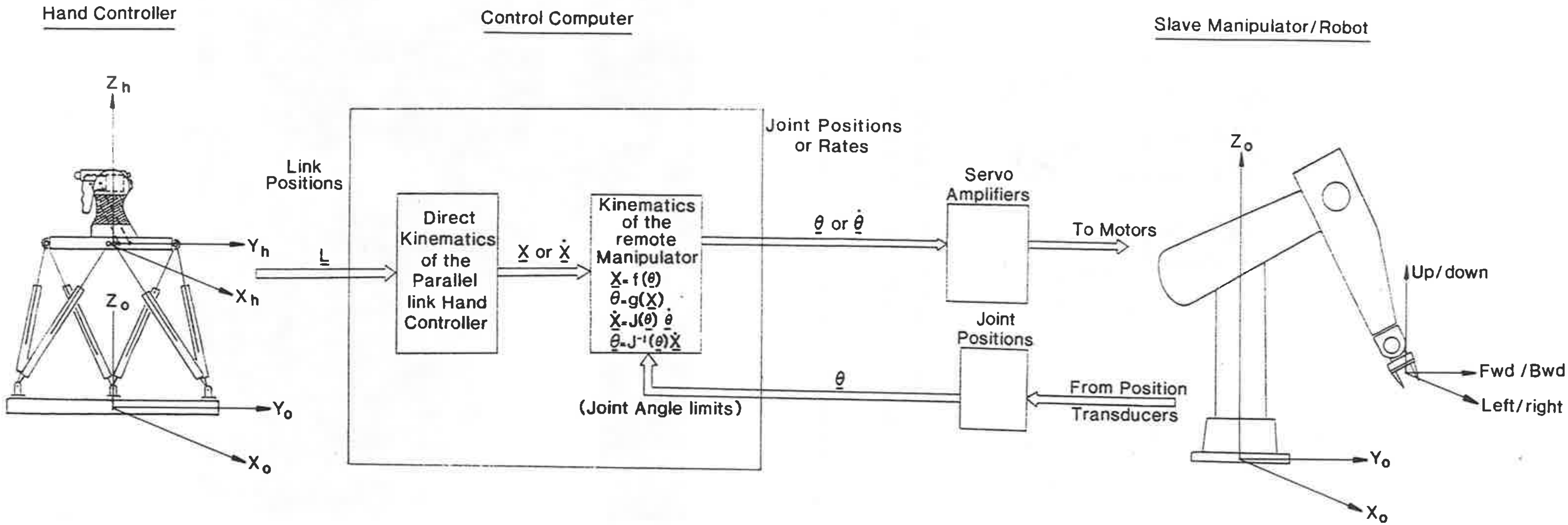
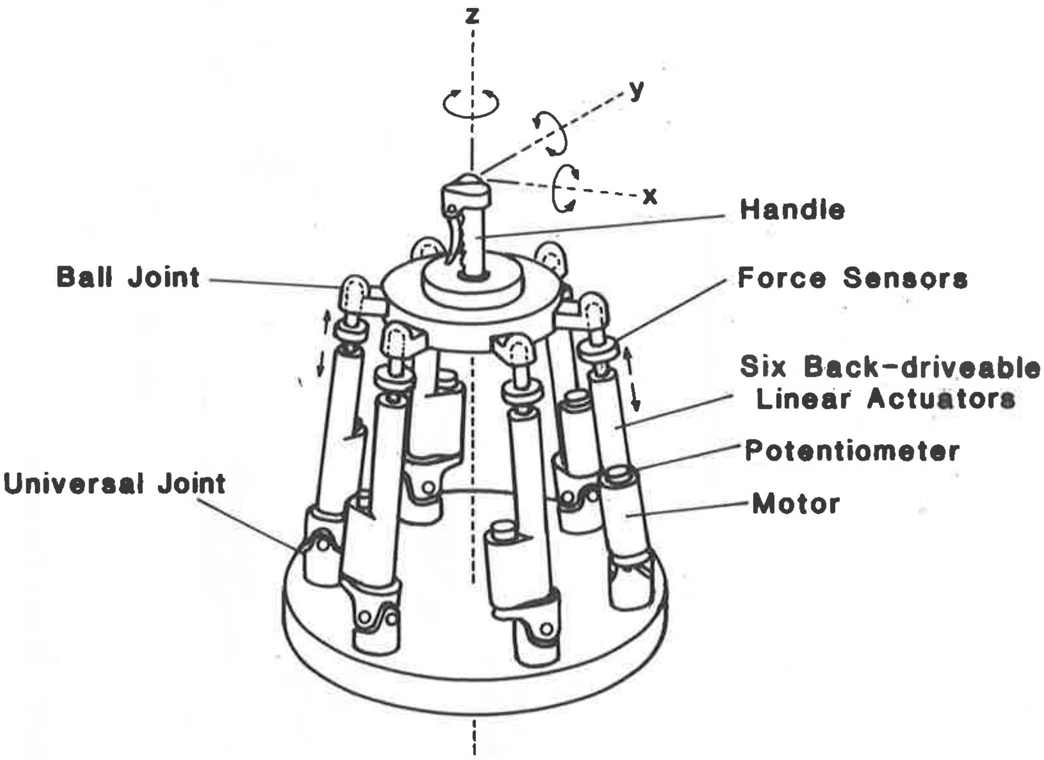



Fig.7 Unilateral Control of the Remote Manipulator Using the Parallel Link Hand Controller




Stewart Platform Configuration
(as a 6 Degrees of Freedom Joystick)

Fig.9 Hand Controller Based on Parallel Link Mechanism

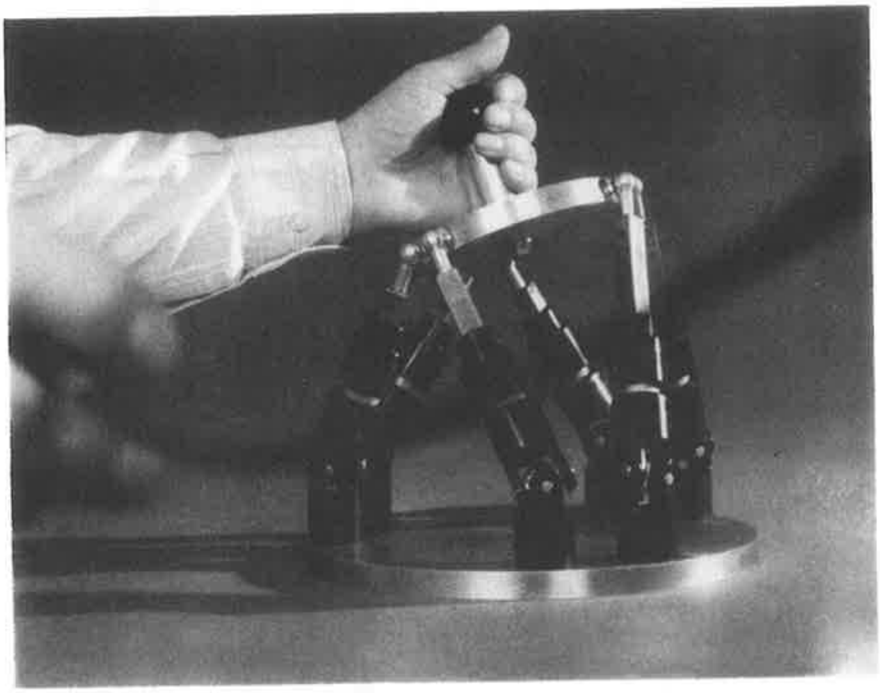


Fig.10 Mock-up of the 6-Axis Parallel Link Joystick

## References

1. "Kinesthetic Coupling between Operator and Remote Manipulator", by A K Bejczy et al, Proc ASME Computer Technology Conference, San Francisco, August 1980.

2. "Joint Co-ordination for Manipulator Tracking", by T Turner, Proc 20th IEEE Conference on Decision and Control, San Diego, December 1981.

3. "Dynamic Stabilization Methods for Bilateral Control of Remote Manipulation", by M Handlykken, Proc of ISMM Symposium, San Francisco, May 1981.

4. "Human and Computer Control of Undersea Teleoperators", by T B Sheridan et al, MIT Man-Machine System Laboratory Report, July 1978.

5. "CEGB Work on In-Reactor Maintenance Techniques", by S B Hosegood, Proc of the 29th Conference on Remote Systems Technology, 1981.

6. "Computer Augented Manual Control of Remote Manipulators", by R E Shultz et al, Proc of IEEE Conference on Decision and Control, San Diego, January 1979.

7. "An Interactive Animated Display of Man-Controlled and Autonomous Robots", by C D Crane et al, Proc of the 1986 ASME Computers in Engineering Conference, Chicago, July 1986.

8. "CAE - 6 Axis Controller", Product Catalogue, CAE Electronics Ltd, Quebec, Canada.

9. "Direct Digital Robot Control using a Force-Torque Sensor", by G Hirzinger, IFAC Real Time Digital Control Applications, Mexico, 1983.

10. "Remote Manipulator Control with Six Degrees-of-Freedom Force-Torque Joystick", Product Catalogue, JR3 Inc, Woodland, California, USA.

11. "Force-Torque Spacestick", Product Catalogue, Basys Systemsoftware mbH, Nurnberg, West Germany.

12. "The CEGB Advanced Robotics System Developments for In-Reactor Inspections and Repair", by D W Perratt, Proc of the Int Workshop on Nuclear Robotic Technologies, University of Lancaster, July 1987.

13. "Two 3-Axis Joysticks for the Control of the Control of PUMA Robots", Private Communication with P J Fischer, Harwell Laboratory, Oxford, UK.

14. "A Platform with Six Degrees of Freedom", by D Stewart, Proc Inst Mech Engrs, Vol 180, No 15, London, 1965.

15. "GEC Advanced Device for Assembly", by S L Potton, Manufacturing Systems, Vol 13, No 2.

16. "A Compliant Device for Inserting a Peg in a Hole", by H McCallion et al, The Industrial Robot, June 1979.

17. "On Machine Perception of the Relative Position of Two Objects using Bilateral Tactile Sensing Systems", by H McCallion et al, Proc Inst Mech Engrs, Vol 1988, No 10, 1984.

18. "Cross-coordinate Control of Robotic Manipulators", by J R Jones, Proc of the Int Workshop on Nuclear Robotic Technologies and Applications, University of Lancaster, July 1987.

19. "Feasibility Study of a Platform Type of Robotic Manipulator from a Kinematic Viewpoint", by D C H Yang et al, Trans ASME J Mechanisms, Transmissions and Automation in Design, Vol 106, 1984.

20. "Parallel Manipulators - Part I, Theory, Design, Kinematics, Dynamics and Control", by Jean Pierre Merlet, Research Report No 646, INRIA, France, March 1987.

21. "Instantaneous Kinematics of Fully Parallel Devices", by M G Mohamed et al, Proc of the 6th World Congress on Theory of Machines and Mechanisms, New Delhi, India, 1983.

22. "Determining the Motions of Joints on a Parallel Connection Manipulator", by E F Fichter et al, Proc of the 6th World Congress on Theory of Machines and Mechanisms, New Delhi, India, 1983.

23. "A Stewart Platform Based Manipulator: General Theory and Practical Construction", by E F Fichter, Int J of Robotics Research, Vol 5, No 2, 1986.

24. "Structural Kinematics of In-Parallel-Actuated Robot Arms", by K H Hunt,Journal of Mechanisms, Transmissions and Automation in Design, Vol 105, December 1983.

25. "The Analysis of a Six Degree-of-Freedom Work Station for Mechanised Assembly", by H McCallion et al, Proc of 5th Congress on Theory of Machines and Mechanisms, Montreal, July 1979.

26. "Hand Controllers for Teleoperation", by T L Brooks et al, JPL Publication 85-11, March 1985.

The problem of inverse kinematics is more straightforward for a parallel link manipulator than for a serial link manipulator. Therefore, the problem of finding the link lengths for a given position and orientation of the top platform based on Yang's [19] method is outlined first.

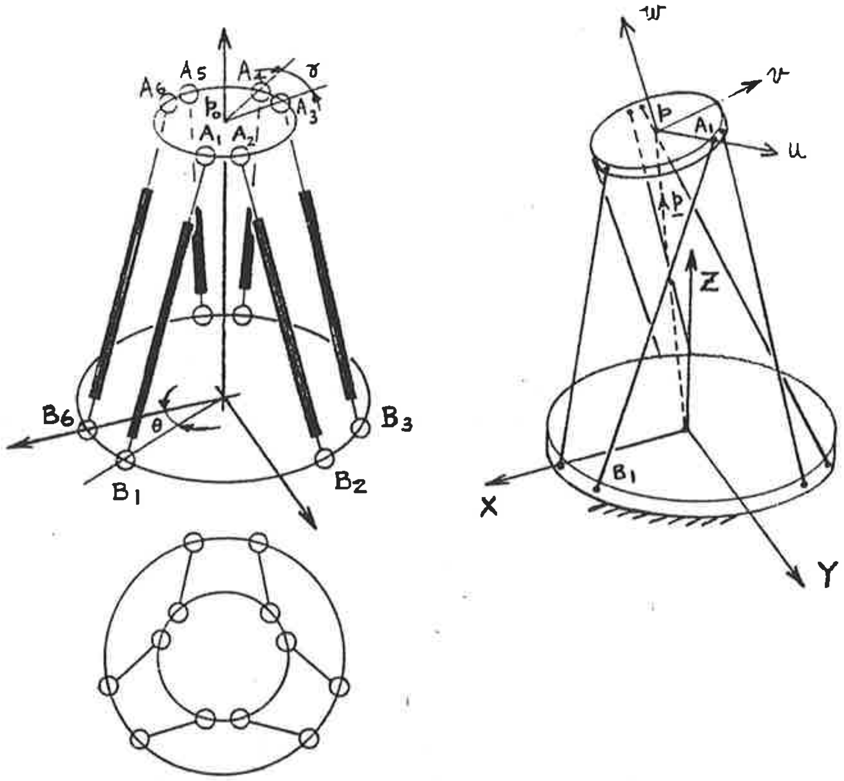



Fig 11 : Definition of the Co-ordinate Frames

Denoting R and r as the radii of the bottom and top plates respectively, $\ell_o$ as the nominal length of the legs or links and h as the distance between the plates when all leg lengths are equal to $\ell_o$; $\ell_1$ through $\ell_6$ as the varying leg lengths; $A_1$ through to $A_6$ as the locations of the ball joints in the top plate and $B_1$ through $B_6$ as the locations of the universal or Hooke joints in the bottom plate; X-Y-Z as the fixed co-ordinate frame of the bottom plate and u-v-w as the moving co-ordinate frame of the top plate.

The locations of the ball joints and universal joints can now be expressed in their respective co-ordinate frames, as follows:

$$A_1 = [r,o,o]^t \qquad B_1 = [R,0,0]^t$$

$$A_2 = [r\ C_\gamma, r\ S_\gamma, o]^t \qquad B_2 = [R\ C_\theta,\ R\ S_\theta, 0]^t$$

$$A_3 = [r\ C_{120}, r\ S_{120}, 0]^t \qquad B_3 = [R\ C_{120},\ R\ S_{120}, 0]^t$$

$$A_4 = [r\ C_{120+8}, r\ S_{120+8}, 0]^t \qquad B_4 = [R\ C_{120+\theta},\ R\ S_{120+\theta}, 0]^t$$

$$A_5 = [r\ C_{240},\ r\ S_{240}, 0]^t \qquad B_5 = [R\ C_{240},\ R\ S_{240}, 0]^t$$

$$A_6 = [r\ C_{240+\gamma},\ r\ S_{240+\gamma}]^t \qquad B_6 = [R\ C_{240+\theta},\ R\ S_{240+\theta}, 0]^t$$

where $\gamma$ is the angle between ball joints $A_1$ and $A_2$ and so on; and $C_\gamma$ and $S_\gamma$ represents Cos $\gamma$ and Sin $\gamma$ respectively. Similarly $\theta$ is the angle between $B_1$ and $B_2$ and so on.

The position of the platform relative to the fixed base can be defined by a vector $\underline{p}$ which is a position vector from the origin of the base co-ordinate system X-Y-Z to the origin of the platform co-ordinate system u-v-w:

$$\underline{p} = (p_x \ p_y \ p_z)^t$$

Similarly, the orientation of the platform relative to the base can be defined by a rotation matrix R:

$$R = \begin{bmatrix} \alpha_x & \beta_x & \gamma_x \\ \alpha_y & \beta_y & \gamma_y \\ \alpha_z & \beta_z & \gamma_z \end{bmatrix}$$

Where $(\alpha_x, \alpha_y, \alpha_z)$, $(\beta_x, \beta_y, B_z)$, and $(\gamma_x, \gamma_y, \gamma_z)$ are the direction cosines of the axes u, v and w with respect to the fixed X-Y-Z co-ordinate system. The geometrical relationship between the fixed co-ordinate frame and the moving co-ordinate frame is usually represented by a 4x4 homogeneous transformation matrix as follows:

$$[T]_p = \begin{bmatrix} \alpha_x & \beta_x & \gamma_x & p_x \\ \alpha_y & \beta_y & \gamma_y & p_y \\ \alpha_z & \beta_z & \gamma_z & p_z \\ o & o & o & 1 \end{bmatrix}$$

The location of each ball joint ($A_1$ through $A_6$) on the moving top platform with respect to the fixed co-ordinate frame can now be obtained as:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{A1} = [T]_p \begin{bmatrix} r \\ o \\ o \end{bmatrix} \quad \text{and so on}$$

The link lengths can be obtained by calculating the distance between the corresponding pair of joints in the moving top plate and the fixed base. For example:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{A1} = \begin{bmatrix} \alpha_x \ r + x_p \\ \alpha_y \ r + y_p \\ \alpha_z \ r + z_p \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{B1} = \begin{bmatrix} R \\ o \\ o \end{bmatrix}$$

Hence, $l_1^2 = (\alpha_x \ r + x_p - R)^2 + (\alpha_y \ r + y_p)^2 + (\alpha_z \ r + z_p)^2$.

The above form therefore represents a set of explicit input-output equations for the inverse kinematics of the parallel link mechanism. It can also be seen that the direct kinematics problem involves the solution of a set of non-linear simultaneous equations.