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DESIGN, CONSTRUCTION AND CONTROL OF A REMOTELY OPERATED VEHICLE (ROV)

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ABSTRACT

This is report of design, construction and control of "Ariana-I", an Underwater Remotely Operated Vehicle (ROV), built in Shiraz University Robotic Lab. This ROV is equipped with roll, pitch, heading, and depth sensors which provide sufficient feedback signals to give the system six degrees-of-freedom actuation. Although its center of gravity and center of buoyancy are positioned in such a way that Ariana-I ROV is self-stabilized, but the combinations of sensors and speed controlled drivers provide more stability of the system without the operator involvement. Video vision is provided for the system with Ethernet link to the operation unit. Control commands and sensor feedbacks are transferred on RS485 bus; video signal, water leakage alarm, and battery charging wires are provided on the same multi-core cable. While simple PI controllers would improve the pitch and roll stability of the system, various control schemes can be applied for heading to track different paths. The net weight of ROV out of water is about 130kg with frame dimensions of 130×100×65cm. Ariana-I ROV is designed such that it is possible to be equipped with different tools such as mechanical arms, thanks to microprocessor based control system provided with two directional high speed communication cables for on line vision and operation unit.

I. INTRODUCTION

From the first digitally operated and programmable robot, the "Unimate", installed in 1961 to lift hot pieces of metal from a die casting machine and stack them in GM up to now, robots become essential part of modern industries. In many applications robots are operating more accurate and reliable than man operation, and cheaper. Specifically in offshore and marine industry, human operations are limited due to the constraints on the operation time, accuracy, risks, and pressure under the water.

There has been a rising interest in the development of autonomous submarine robots capable of roaming the oceans freely and collecting data on the surface on an unprecedented scale. Recent progresses in sensors, actuators, communications, computers hardware and software systems have been lead to submarine robots which provide safer, faster, and far more efficient equipments for exploring the ocean frontier, especially in hazardous conditions.

Typical applications of ROVs in industries and scientific research are: inspection and evaluation of submersed structures, transportation and assembly of underwater equipments, ships rescue, geotechnical and environmental data gathering, dumps or toxic waste location, marine archeology and so on [1].

Unmanned Underwater Vehicles (UUVs) are submarine robots which classified in two main categories: remotely operated vehicles (ROVs), which are tethered, teleoperated, power-supplied underwater vehicles and autonomous underwater vehicles (AUVs) which are completely autonomous units and tether do not use for communication and power supply in this type of underwater robots.

The first ROV named "the POODLE" was developed by Dimitri Rebikoff in 1953 but the US Navy take the first real step to an operational system in order to find torpedoes that were lost on the seafloor [2]. Since then, many ROVs were designed aiming at different goals that range from pure experimental studies to perfect industrial ones. Romeo ROV was designed in 1998 for educational purpose, based on experience from Roby ROV project. It was used to study various issues relating to operation of ROV [3]. VideoRay Pro III micro ROV is a commercial system with an open architecture that accommodates tools and sensors. The ROV has three-thruster arrangement with two horizontal thrusters and one vertical one for its motion control. This ROV has been employed for experimental studies [4]. The Minerva ROV was specially designed by Sperre AS in 2003 to fulfill the needs of scientists at NTNU [5]. With its five thrusters, two vertical, one lateral and two forward thrusters, it can descent to 700 m depth. Gomes, Susa et al. reported design process of KOS ROV. This project was done in USTL at the University of Porto to deal with the weakness point of IES ROV, Especially to achieve greater maneuverability in surge and sway and maintain stability in presence of significant disturbances during the operation at harbors, rivers and sea [6].

In broad terms, robotics and control affected each other mutually and have been progressing in the recent decades. Designing a proper control scheme for ROVs as addressed in the literature. Yoerger and Slotine introduced sliding-mode control and applied adaptive sliding control on a ROV at first experimental case on Jason ROV [7]. Designing high-precision bottom-followers for ROV by use of simple estimator of the vehicle’s altitude and bottom slope based on the measurements of a couple of echo-sounders and results of pool trials with Romeo ROV are presented [8]. The tracking in JHUROV ROV uses a linear proportional-derivative (PD) controller and a family of fixed and adaptive model-based controllers is reported [9]. Walchko, Novick and Nechyba applied sliding mode control to Subjugator ROV [10].

In addition to experimental investigations, there are a large number of theoretical and simulation studies on regulation, dynamic positioning and tracking of underwater robots. In these studies more complicated algorithms were designed to face a number of complexities such as considering inherently nonlinear dynamics, time-varying and undeterministic hydrodynamic parameters, disturbances caused by underwater currents and etc [11-14].

This paper provide a report of design, construction process and controlling a laboratorial ROV called Ariana-I. The main Objective behind developing Ariana-I is to provide Control Lab. of Shiraz University with a test-bed to study advanced control and underwater navigation. The second goal of this project is to implement a prototype ROV for visual inspection of submarine pipelines and power cables of oil platforms. That’s why we have provided video on Ethernet to install Megapixel Digital, high sensitive camera in actual test of the ROV in sea.

In the next section design and construction process of Ariana-I ROV is described. In the third section, a brief explanation dynamics equations of motion the underwater vehicles is illustrated. In section 4 autopilot control design is reported. Experimental results are shown in section 5 and conclusions and project planning can be found in section 6.

II. DESIGN AND CONSTRUCTION

According to the project's goal, The ROV should meet the following requirements:

1. An ROV with six degrees-of-freedom actuation capability, with fully waterproof parts.
2. All six degrees of freedom are required to be observable with appropriate set of sensors.
3. The ROV should provide vision system to enhance pilot dexterity and the feeling of telepresence.
4. Control commands should be applied to the robot through a tether cable from an operation console (laptop) located at the surface. Sensor and vision signals also have to be transferred to the operation console through the same means.
5. It would be possible to add other modules to the frame for special applications.
6. The ROV cost is required to remain reasonable for this laboratorial project compared to commercial ones.

A. DESIGN CONCEPTS

The first step in designing our ROV was to select proper thrusters. Two reasons behind this selection were impacts on overall cost and size of the ROV. Our final decision for thrusters has been sea-scooter thrusters.

Then we started through a successive process to determine the size of the frame of the ROV and other parts and positioning of the parts according to design considerations which is briefly described in section (E).

One of the main requirements at this stage was to develop the frame to be able to mount extra modules which carry equipment such as intervention manipulators with various end effectors (Fig . 1).

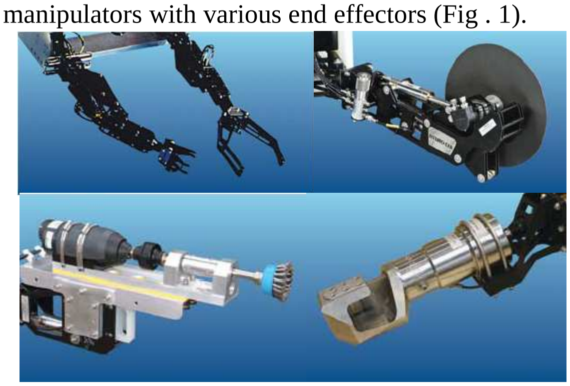


Fig. 1. Some extra equipment which are added to ROV frame for special applications [11]

To achieve this requirement, we designed a base frame. Base frame with the expansion capability should contain basic navigational sensors, video camera and processors. Taking into consideration possible extra modules and thrusters size, we came at the approximate size of the overall base frame which is 130×100×65 cm. In the next step, we selected frame material as well as the fixtures for different parts. Design requirements imposed us to a specific material which is discussed in section (D).

The most important part of the design was thrusters' arrangement and distribution. The need for compensation against different disturbances and also decreasing the undesirable effect of jet-to-jet and jet-to-structure interactions were our main concerns in this stage. After selecting thrusters' distribution to meet the requirements and constraints, based on the selected material different parts of the ROV were designed and their positions were tested in the software. In the ROV structure the center of gravity and the center of buoyancy were intended to happen in such a way that it became passively stable. In order to position in the center of buoyancy, the system was designed to configure by the operator in order to meet the acceptable level of passive stability. These design criteria are discussed in next sections.

Our final design is illustrated in Figure 2. In the remainder of the paper we detail each part and design considerations.

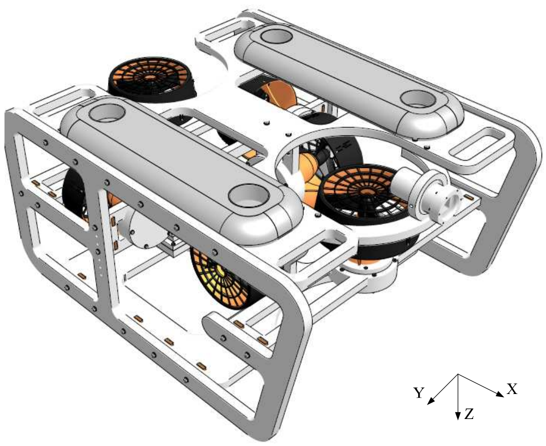
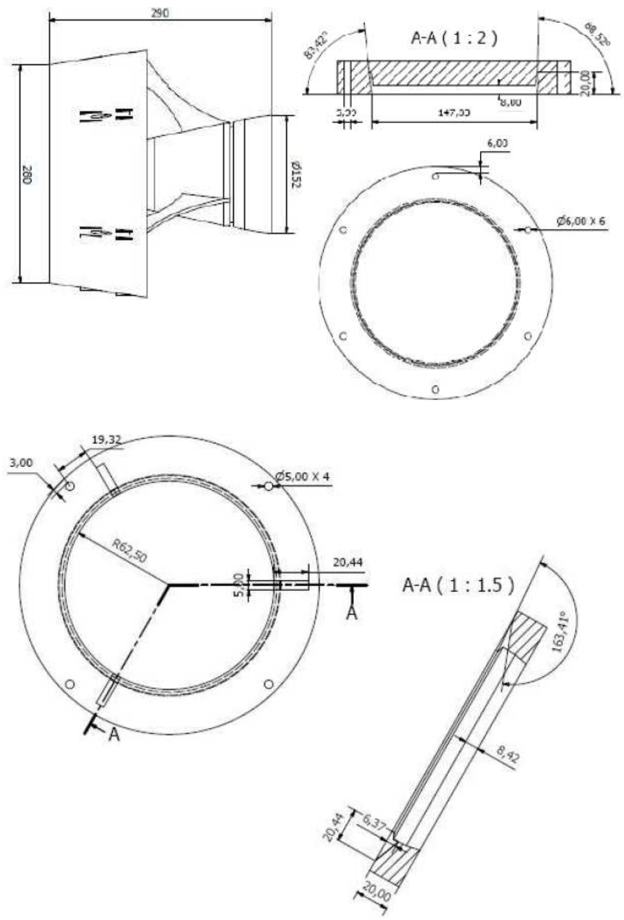


Fig. 2. Ariana-I ROV

B. THRUSTERS

In Ariana-I ROV sea-scooter thrusters (Fig. 3) are used as the actuators of the ROV, although the best choice for the thrusters of designed ROV are the brushless DC motors to achieve minimum dimension for the same power rating. These scooters have been selected mainly because this version of the robot is the educational one and scooters satisfy desired conditions of this type of ROV. Some changes have applied to the sea-scooter to use it as the thruster in the ROV. The sea-scooters drivers are replaced with other smart electronic driver. Buoyancy and battery casings are removed and the scooter is waterproofed as shown in the Figure 4.

Fig. 3. Sea-scooter which used as the ROV actuators



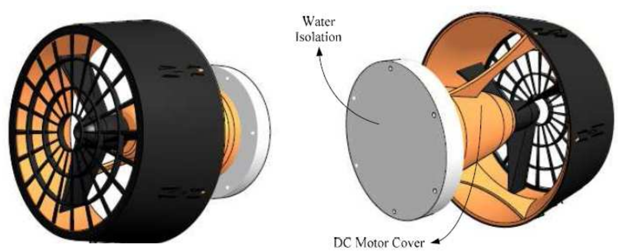


Fig. 4.a. Sea-scooters are waterproofed and assembled to the thruster chassis

Fig. 4.b. Sea-scooters are waterproofed and assembled to the thruster chassis

C. THRUSTER DISTRIBUTION

There are two widespread conventional thruster distributions for industrial ROVs. Regarding the fact that in most industrial applications surge, heave and yaw motions are satisfactory, only three thrusters would meet the demand. In the so called three-thruster arrangement two thrusters supply parallel propulsion for surge motion which also give yaw moment in differential mode and one thruster to propel the vehicle for heave motion (Fig. 5. a). The other common distribution provides the same 3 degrees of freedom with more actuators (Fig. 5. b).


(a)


(b)

Fig. 5. (a) VideoRay Pro 3 XE GTO ROV (b) Falcon ROV

These arrangements are prone to lose roll and/or pitch stability in the case of significant asymmetric loads and disturbances if righting moment could not compensate for these loads. To deal with these weakness points, some educational ROV designs were proposed. Among those is ROV of Johns Hopkins ROV, JHUROV [9].

We design the ROV with six thrusters which are used in a configuration illustrated in Figure 6. This arrangement could overcome those mentioned drawbacks with conventional designs. In our design, there are two thrusters in the X-axis direction to provide surge motion and yaw angle rotation (heading motion), two thrusters in the Y-axis direction to provide sway motion and roll rotation and two actuators in the Z-axis for heave motion and pitch rotation.

This kind of thruster distribution gives the system the ability to change its equilibrium state. To illustrate, thrusters 4 and 5 could make non-zero roll equilibrium state. The same is true for pitch angle with thruster 1 and 6.

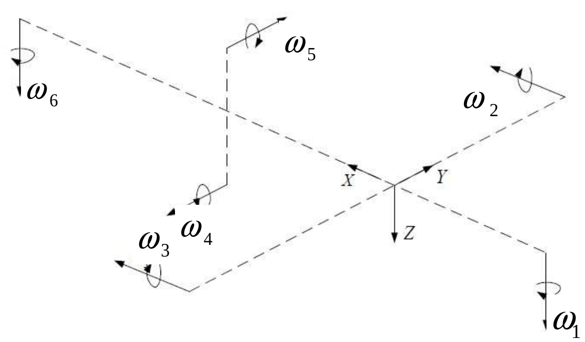


Fig. 6. The distribution of the thrusters in the ROV frame

D. MATERIAL SELECTION

The properties of material used in the project are:

1. It is preferred to select the materials whose density is near to water density for the frame and buoyancy system in order to have a neutral buoyant vehicle.
2. Since some of the selected sensors work based on the earth magnetic field, materials should have low magnetic properties not to influence the output of the sensors.
3. Materials should resistive to the water corrosion.
4. Easily available materials in marked are used in this ROV.
5. Materials should be machined and formed easily to perform desired plan.

Table 1 present the material which have been used in the project.

	material	density(kg/m^3)	Young's modulus(Pa)	thermal conductivity(W/(mc))
1	ABS	1060E+003	2890E+009	0.299
2	PVC	1.400E+003	2.585E+009	1.785
3	Bronze	8.874E+003	1.096E+011	62.000
4	SS 316	7.750E+003	2.067E+011	16.000

Table 1. List of the selected materials and their properties

E. FRAME

The main frame and thrusters' chassis of the ROV are made from ABS plate. It is the open frame like common industrial ROVs' structures. Dimensions of the frame are $130 \times 100 \times 65\ cm$. Construction procedure is:

1. In the first stage, the 2D sketch of the part would draw on the ABS plate.
2. In second stage, the general shape of the part is cut by the saw.
3. In last stage, the final shape of components is prepared by milling.

The frame of the ROV is consist of two side plates (Fig. 7), top plate (Fig. 8), down plate (Fig. 9) and thrusters' chassis (Fig. 10). These steps are appeared in [11].

The design considerations for the frame are:

- Simplicity and rigidity
- Symmetry in thrusters' distribution to minimize undesired reaction moments.
- The vehicle should be nearly neutrally buoyant and the center of buoyancy should be placed above the center of gravity to generate righting moment.
- It would be possible to add extra module, for example the module for robotic arm with different end-effectors to the bottom of the side plates of the frame.

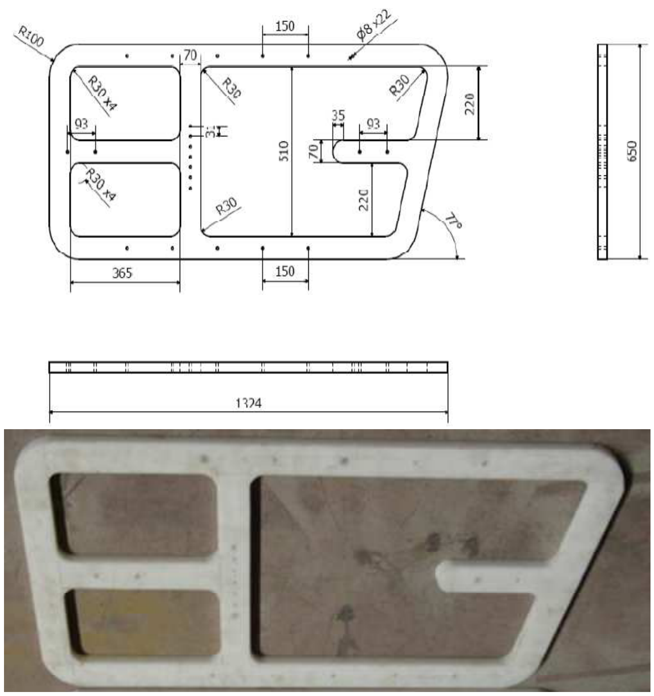


Fig. 7. Side part of the ROV frame

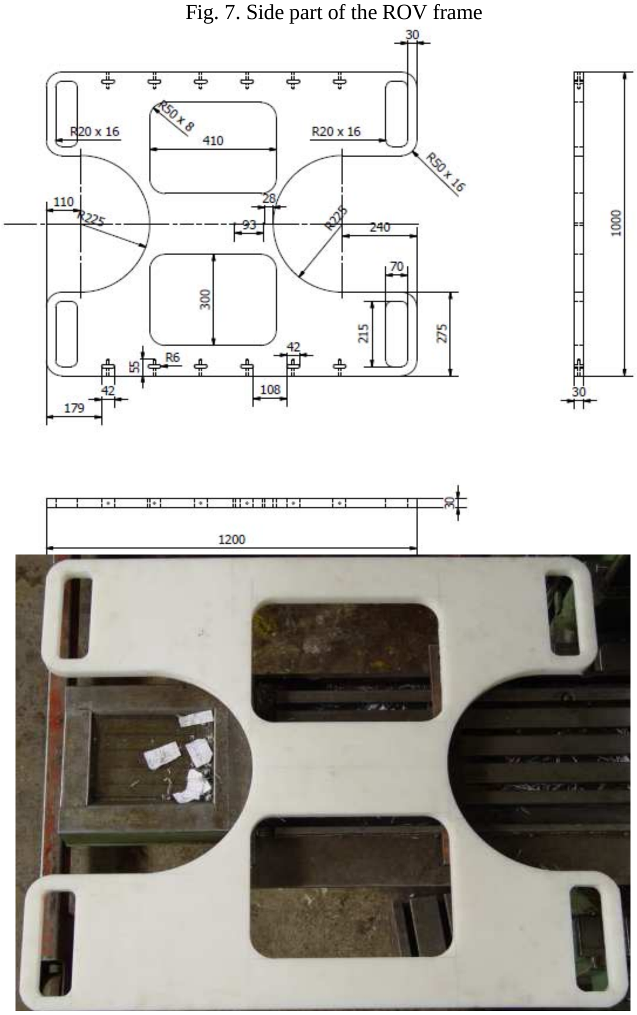


Fig. 8. Top plate of the ROV frame

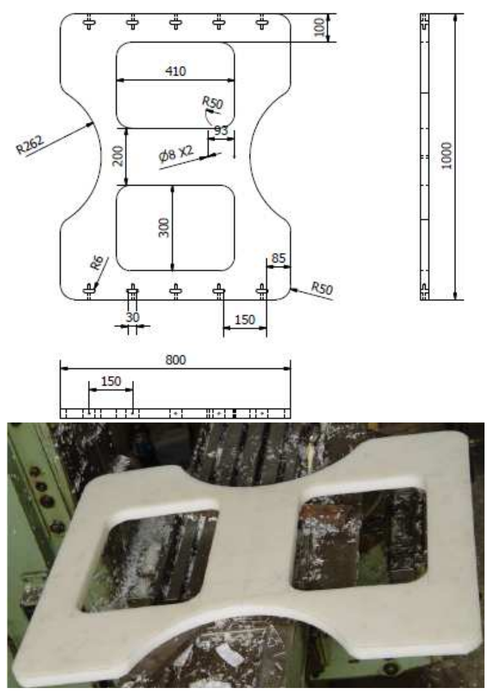


Fig. 9. Down plate of the ROV frame

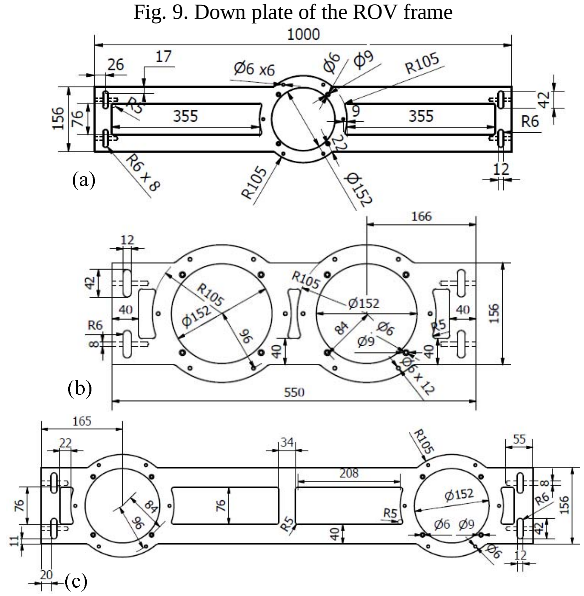


Fig. 10. (a) Chassis of thrusters no. 4,5, (b) Chassis of thrusters no. 1,6, (c) Chassis of thrusters no. 2,3.

F. BATTERY AND ELECTRONIC BOARD CASE

The battery and Smart electronic board case is made of ABS and consist of three parts, parts are fixed together by bolts and nuts and water proofed using O ring between them. The sketch of the case is shown in Figure 11.

The volume of the box is $370 \times 370 \times 150\ mm^3$ and it contains six 24VDC sealed acid batteries and electronic board. Batteries are placed in the bottom, and board is located in the top part of the box.

Because of high thermal conductivity of the body, the head cover of the box is made of bronze to send out the heat generated by the electronic board.

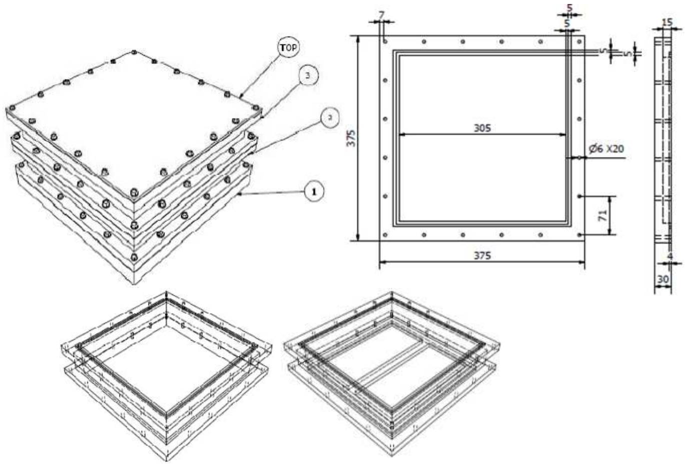


Fig. 11. Battery and board case

G. BUOYANCY SYSTEM

Fundamentally the mechanical system design includes determining proper configuration for its dynamic and hydrodynamic parameters and also the flexibility in buoyancy system in order to maintain neutrally buoyant situation and also the suitable position for center of mass and center of buoyancy.

We address the problem in two steps. Firstly, we model the ROV components and assemble them in the INVENTOR program such that the position of the center of buoyancy and center of mass make passively roll and pitch stability. In the design it was desirable to have 0.3m meta-centric height and no offset in the x or y axes direction between center of gravity and center of buoyancy. In this step the size of the buoyancy parts and also the location of other components would set up. Whilst the computational modeling and simulation yield to exact plan's dimensions, it should be admitted that in the construction process some uncertainties would be inevitable. Errors would occur in terms of human error, machine error and etc. This restriction has made it necessary for us to design a buoyancy system which contains some modules which can add or remove from the frame. Also it should be possible to move the center of buoyancy and center of mass to meet the optimum state. Lastly, the passive stability and neutral buoyancy would achieve by iterative practical process in the pool.

The net weight of the vehicle out of water is about 130kg. The main component of buoyancy system is consists of two tanks which made of PVC plates and pipes (Fig. 12).

In addition, four cylinders made of PVC pipe which waterproofed could add to the system. Two cylinders are mounted in the longitudinal direction and the other ones established in the lateral direction on the top plate.

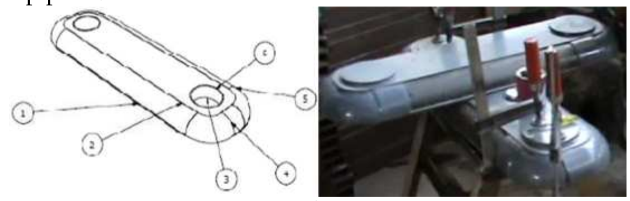


Fig. 12. Buoyancy tanks made from PVC pipes and plates

It is possible to slide the pipes along the direction they mounted, which leads to movement of the center of buoyancy in the longitudinal and lateral and also downward/upward directions. Furthermore, we use four cylindrical case made of PVC and attach them to the four corners of the down plate. Ballasting weights could add to these cases in order to maintain the desired hydrostatic equilibrium, moving the position of center of gravity in longitudinal and lateral direction and also move it downward or upward. Employing this buoyancy system would make it possible to achieve neutral buoyancy and the optimum position for center of mass and center of buoyancy and reduce or increase the meta-centric height.

H. POWER AND PROPULSION SYSTEM

To provide propulsion for the ROV in six DOF, six 80 watts DC motor are used in the configuration described in previous section. Motor maximum current is 3 amperes in full load with maximum rotation speed of 400 RPM on the propeller. Three DC motor double-drivers from Sabertooth are used to drive the motors. Drivers return power to the batteries anytime a deceleration or motor reversal is commanded, which can lead to improvement in run time. To provide power for the whole system, six Lead-Acid 24 V/6 Ah batteries are operating in parallel in the sealed box. Although they are not the best choice considering energy storing density, their availability and low price made them acceptable for our educational project. It is possible to charge the Batteries during operation through a pair of cable over the tether. To provide regulated power for video camera and other electronics, a highly efficient DC/DC converter MPW1033 is used. This converter provides a 12V for the Camera and feeds the regulated 5V & 3.3V power supplies for other electronic parts.

I. NAVIGATION AND CONTROL SYSTEM

Ariana-I can operate autonomously using an onboard autopilot with the given set of onboard sensors. In this case the operator only sends high level commands. The autopilot is mainly based one Atmel AVR microcontroller which is interfaced with all electronics modules and sensors in the ROV (Fig.

13). The sensors include a pressure transmitter Type 691 from Huba for sensing depth, a 3-axis accelerometer ADXL335 from Analog Devices and a 2-axis Inclinometer sensor from Turck. Interfacing to these sensors are provided using microcontroller ADUC8041 from Analog Devices. The processed data is transferred over RS232 link to the autopilot main controller (AVR microcontroller). For the orientation and attitude of the ROV, an HMR3300 module is also added. Besides the heading information, HMR3300 provides roll and pitch data which is the backup of the data sensed by Turck inclinometer.

The AVR microcontroller is responsible for gathering data from sensing modules and generating commands to the actuators, i.e. closing the loop to operate ROV autonomously. Closed feedback control loops are implemented in the onboard AVR microcontroller for different axes. Manual Commanding actuators is also possible. The operator is able to take control of the ROV and overrides the AVR auto commands. In the appropriate intervals the AVR microcontroller sends sensors data over a RS485 bus to the Surface Control Console (SCC). This link makes the implementation of advance control strategies possible from SCC. It is especially helpful in prototyping and testing different control schemes on SCC.

To warn the operator of water leakage three water leakage sensors are devised in different location in the electronics compartment and battery box. Sensors are operating based on water conductivity. In the case of water leakage the conductivity of water drives a buzzer in surface control station, so that operator can shut down the sensitive electronics and command the ROV upward quickly.

Other than those set of onboard sensors a video camera is mounted in front of the ROV. Video Signal is converted to Ethernet and transferred by a single cable between the ROV and control consol.

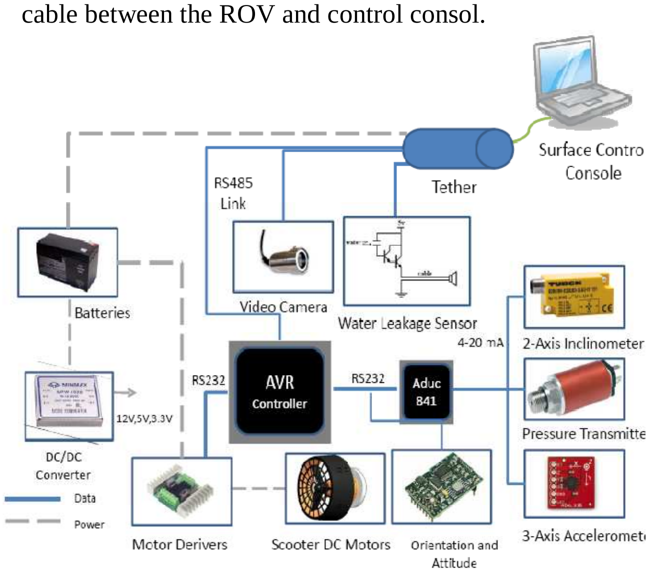


Fig. 13. Schematic view of the autopilot system

J. SURFACE CONTROL CONSOLE

The operator can interact with the ROV using a surface control console (SCC) composed by a graphical user interface (Fig. 14) and an RS485 link for communication. This allows to:

1. **Monitor the state of the ROV** during operation and gives visual feedback to the operator. The ROV's attitude and heading are displayed graphically on virtual instruments. Also the information such as heading, roll and pitch and depth are also displayed on adjustable time.
2. **Activate or deactivate onboard controller** and edit parameter of the controller that is running on-board to tune them directly during the operation.
3. **Give trajectory commands** and other high level set points.

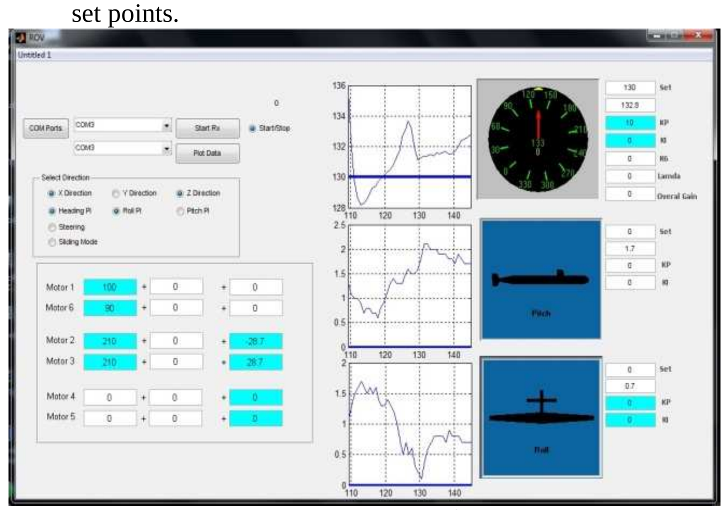


Fig. 14. Ariana-I graphical user interface

III. DYNAMIC EQUATION OF MOTION

In general, ROVs in the water would have at most six degree of freedom; three rotations and three translational motions. Dynamic equations of motion of ROVs could be written in two coordinate frames, body-fixed frame and earth-fixed frame. Both coordinate systems are shown in Figure 15.

The 6-DOFs dynamic equation of motion of underwater vehicles is:

$$\begin{aligned} &M\dot{v}+C(v)v+D(v)v+g(\eta)+P=\tau \\ &\dot{\eta}=J(\eta)v \\ &M\triangleq M_{RB}+M_A; C(v)=C_{RB}(v)+C_A(v); \end{aligned} \quad (1)$$

here M_{RB}, C_{RB} and τ_{RB} are the inertia matrix, coriolis and centripetal matrix and the vector of external forces and moments acting on the vehicle. M_A is the inertia and added mass matrix and $C_A(v)$ is added mass coriolis and centripetal matrix which derived from M_A as discussed in [19].

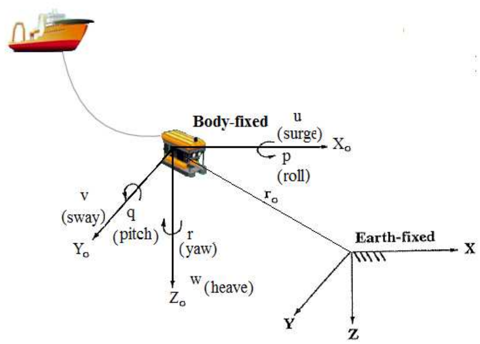


Fig. 15. Body-fixed frame and coordinate-fixed frame

$D(v)$ represents hydrodynamic damping matrix and restoring forces vector in shown by $g(\eta)$. P is the vector of disturbances and noises exerted on the vehicle and τ include actuators forces and moments. , $J(\eta)$ is the Jacobean matrix which is derived from the product of three rotation matrices that transform Body-fixed coordinate frame to Earth-fixed coordinate frame.

The earth-fixed coordinate frame representation can be obtained by applying kinematic transformation [19] to eliminate v and $\dot{v}$ from (1):

$$M_\eta(\eta)\ddot{\eta}+C_\eta(v,\eta)\dot{\eta}+D_\eta(v,\eta)\dot{\eta}+g_\eta(\eta)+P_\eta=\tau_\eta \qquad (2)$$

Modeling the ROV in the INVENTOR gives the following values for M_{RB}, g (η):

$$M_{RB}=\begin{bmatrix}130 & 0 & 0 & 0 & 0 & 0\\ 0 & 130 & 0 & 0 & 0 & 0\\ 0 & 0 & 130 & 0 & 0 & 0\\ 0 & 0 & 0 & 20.27 & -0.0034 & -0.0044\\ 0 & 0 & 0 & -0.0034 & 28.89 & -0.3\\ 0 & 0 & 0 & -0.0044 & -0.3 & 22.83\end{bmatrix}$$

$$g(\eta)=\begin{bmatrix}0 & 0 & 0 & -382.4c\theta s\phi & 382.4s\theta & 0\end{bmatrix}^T$$

As observed in the rigid body inertia matrix, off diagonal terms are less than diagonal ones and we incorporate their effect to the disturbance vector P. if we assume M_{RB} is symmetric then C_{RB} will be:

$$C_{RB}(v)=\begin{bmatrix}0 & 0 & 0 & 0 & -130w & 130v\\ 0 & 0 & 0 & 130w & 0 & -130u\\ 0 & 0 & 0 & -130v & 130u & 0\\ 0 & -130w & 130v & 0 & -22.83r & 28.89q\\ 130w & 0 & -130u & 22.83r & 0 & -20.27p\\ -130v & 130u & 0 & -28.89q & 20.27p & 0\end{bmatrix}$$

Our final control objective is to design a control scheme which can compensate for uncertainties and disturbances and in the next step it should identify disturbances and feedback their signals to the control law. Consequently, we estimate added mass (M_A, $C_A(v)$) and hydrodynamic matrix ($D(v)$) by strip theory. Identification of hydrodynamic coefficient is also a control objective and addressed in the literature [20, 21].

IV. AUTOPILOT CONTROL DESIGN

At the first step of this project PID-type control law is designed for controlling heading angle. The control law is:

$$\tau_{PID}=K_p\tilde{\eta}(t)+K_d\dot{\tilde{\eta}}(t)+K_i\int_0^t\tilde{\eta}(\tau)d\tau \qquad (3)$$

Where K_p, K_d and K_i are control matrices and they should be diagonal. $\tilde{\eta}=\eta_d-\eta$ represents the tracking error. Most ROV systems for practical applications use only P- and PI-controller for autopilot and depth control [19]. The autopilot procedure is demonstrated in [22]. As it shown when the head angle of ROV would deviate from its set point, angular velocity of thrusters 2 and 3 changed to compensate the deviation. Figure 16 displays the block diagram of PID controller for autopilot regulation control. This architecture is the same as the PID controller of [23].

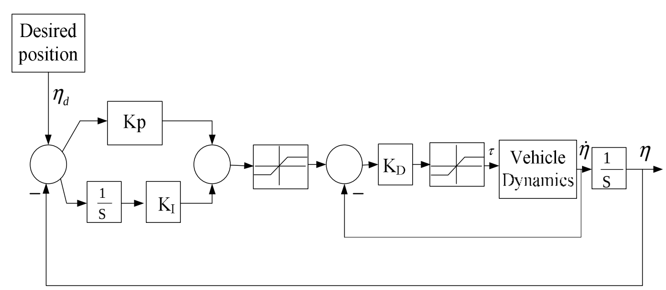


Fig. 16. PID Controller

V. EXPERIMENTAL RESULTS

Here, results of two tests which have been done by implementing the designed controller are presented. These tests consisted of two steps:

1. Firstly, the heading angle set-point was set to make the ROV move along the lane in the middle of the pool
2. After 70 to 75 seconds the heading set-point was changed so that the ROV turned and got back to the first lane.

Figure 17 demonstrates the movement of the robot during the tests. The first experiment was done on the surface of the water while the second one was executed at the depth of 1 to 2 meters.

The heading angle's changes during the time are displayed in Figures 18 and 19. In these experiments PID control coefficients were:

$$K_p=10, K_I=1, K_D=0$$

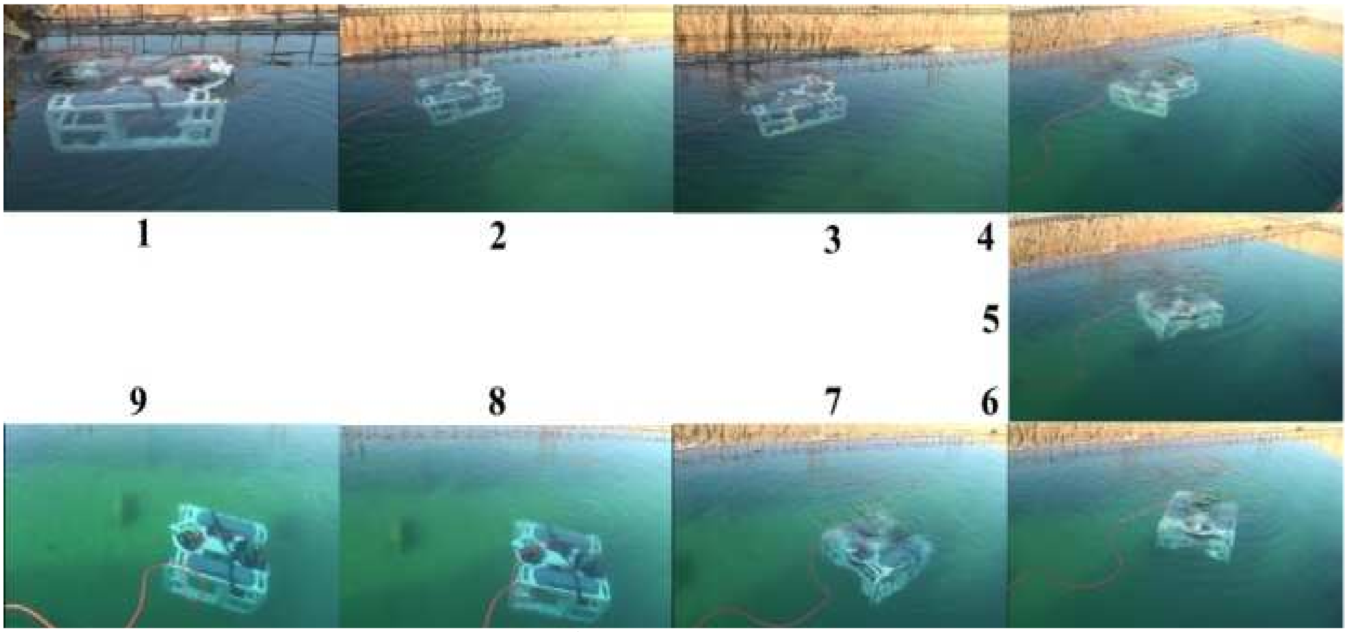


Fig. 17. Movement of Ariana-I ROV during its Operation, test2

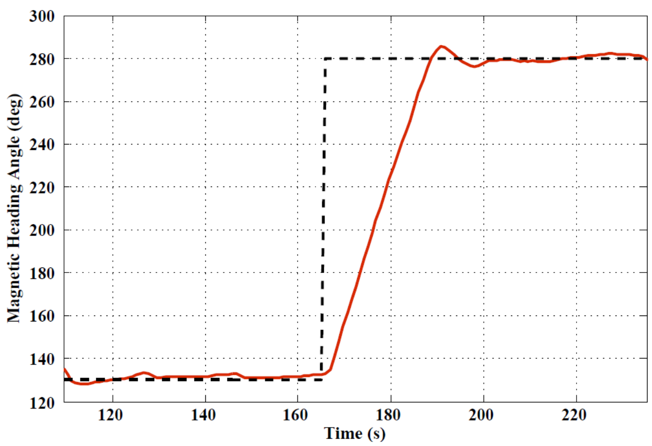


Fig. 18. Heading angle regulation control result by PID control scheme, surface test

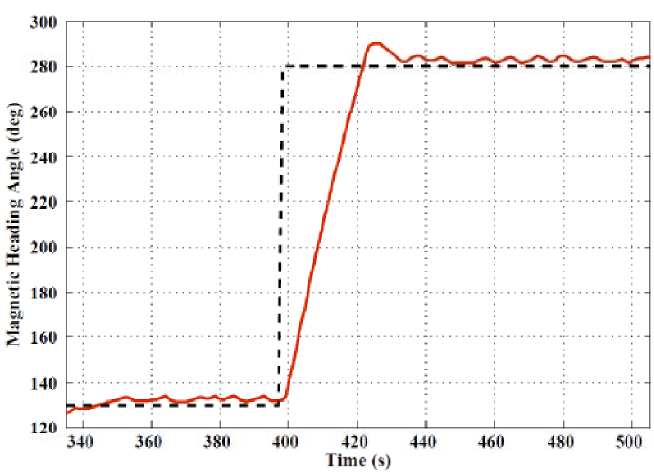


Fig. 19. Heading angle regulation control result by PID control scheme, depth test

Both tests are exhibited in [16].

VI. PROJECT PLANNING AND CONCLUSION

Ariana-I ROV was designed and constructed based on the requirements to provide a test-bed for educational projects. For all six degrees of freedom different control schemes can be applied onboard or on SCC. In the first stage, simple PID controller loops were closed in the onboard autopilot. Heading control loop was closed via SCC. In this case various control designs were applied without the need of stopping the experiment and modifying the onboard autopilot. PI controller is proved to be successful for yaw angle regulations in the pool condition, both for surface and underwater trial.

With the experience accumulated during the tests, one objective is to assess the robustness of different control schemes in presence of disturbances. Sliding mode controller to track different paths is considered as the next stage. Identification of model parameters is planned for future works. Tracking roll and pitch angles are also in our vision.

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