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***Abstract*—This paper presents a high performance autonomous underwater robot under development for inspection of flooded mines up to 500 meters depth. Underwater robots have multiple advanced subsystems and mechanisms. Initial structure design of subsystems and their functions are demonstrated here briefly. In addition, Hydrodynamic coefficients that contribute to robot equation of motion are addressed. The advantage of utilizing spherical design is verified by applying simplification to determine the main coefficient of motion theoretically.**

***Keywords*—Underwater robot, Mechatronic, Control, ROV design**

I. Introduction

Development of underwater robot vehicles extended to advance applications during recent years. Most common applications of underwater robot incorporate in inspection, oceanography, surveying, however recent developments proceed to sophisticated vehicles which are capable of performing multiple tasks simultaneously.

This paper presents early stage mechanical and mechatronic development and vehicle dynamic. It also provides a review of the recent similar projects.

Mainly Underwater Robotic Vehicle (URV) are divided into two categories of Remotely Operated Underwater Vehicle (ROV) and Autonomous Underwater Vehicle (AUV). ROV's are commonly used for long term underwater operation. Latest example of ROV is presented by [1], which transfers the power and data through umbilical cord, has 5 degree of freedom with 6 thrusters. The ROV equipped with DVL, camera, Attitude and Heading Reference System (AHRS), however the main processor units are located outside the operating environment.

AUV is more restricted in terms of operating time as they have limited source of power, however different methods are researched and implemented to lower power consumption. For instance presented in [2] is an AUV equipped with propeller, rudder and elevator and fuzzy logic is implemented for landing strategy to minimize the power consumption. Although the control model haven't been implemented on actual AUV.

AUV has more advance autonomy in terms of control and structure layout while the main controller and power unit are located inside the robot. Mako [3] is the name of 4DOF AUV developed by Australia navy with 4 thrusters. The robot is symmetrical and it equipped with 2 vertical thruster on both end and two horizontal thrusters in the middle. Two hull is designed for the robot, the lower hull carry battery and upper one carries electronic units with 2 main processor, however yet the robot depth operating range is limited to 5 to 10 meters.

Among recent works there has also been innovations in design such as an AUV called Nereus [4], that can be converted to ROV, or design of a water jet systems by Liu [5]. Prior spherical model known as ODIN by choi [6] provide 6 degree of freedom with 8 thrusters, however positioning sonars and thrusters on circumference of the body diminished the solid streamline shape of the vehicle.

The project UNEXMIN investigates to utilize the capabilities of fully autonomous sea robot to prospect flooded mines, where technological challenges hindered human accessibility to mine for years. UNEXMIN "**A**utonomous **Un**derwater **Ex**plorer for Flooded **Min**es" aim to deliver valuable graphical and geological information. The main characteristic of the robot is briefly outlined in table I.

This paper points out three main sections. The first section overviews the general architecture design of robot. Second section describes briefly the hardware layout such as computer and sensors.Third section presents the dynamic equation and parameters to consider for motion of the robot.

II. Architecture Design

The mechanical design of a high performance underwater robot vehicle has been researched and undertook development. The general characteristic of the AUV is demonstrated in table I. The following criteria overviews briefly the comprehensive list of design specification requirements of the robot platform:
1. The robot body should be streamlined to reduce drag and must be at most 60 cm in diameter to be able to drive through narrow underwater channels.
2. The robot must possess high maneuverability while driving through constrained spots
3. The power unit should be capable of supporting the robot for 5 hours of driving autonomously
4. The vision system should be able to map the wall surfaces 360 degree in order to provide $3d$ view
5. The subsystem software module should possess real-time characteristic.

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TABLE I
GENERAL ROBOT SPECIFICATIONS

Features	Specification
Dry hull dimension	sphere 0.60 m Diameter
weight:	≤106 kg
Maximum speed	0.5 m/s
Operating depth	0 to 500 m
Number of thruster	8
Material	Aluminium
Supply Voltage	12-24 v
Control	Autonomous
Maximum pressure	50 bar

The first requirement implies the maximum size of the robot, the maximum volume of the robot can then determines the maximum robot's weight by calculating the buoyancy force. Therefore there should be a compromise between the weight and volume of the robot with regard to components that robot must be equipped. Among various hull design ideas,the sphere profile is chosen because it not only enhances the maneuverability in critical locations, but also the sphere profile can minimize the drag force.

The second requirement implies that robot must be capable of steering. In other word thrusters configuration must be able to produce torque in order to change the robot's heading. The sphere shape eases the installation of thrusters in any spot align with outer surface of robot. As described in section II-B the horizontal thrusters are located at same distance from the center of sphere.

Furthermore the robot is equipped with sonar and several Eo cameras for mapping the environment, however the configuration of vision system is out of scope of this paper.

A. Ballast system

To drive through long vertical shaft up to $500m$, the robot should be equipped with ballast system. There are multiple components such as instrumentation, batteries, controller inside the sphere which allocate up to 4 liters space for ballast inside the sphere. This ballast tank is located at the bottom of sphere. Furthermore, also a cylindrical tube with capacity of 4 liters is considered which can be placed outside on lower semi half circumference of the sphere, however it is not shown in the picture. This tube is protected by a ring shape metal structure with multiples holes, while the tube can expand freely inside it. The volume of the tube can be controlled by pumping the hydraulic fluid inside it, while the robot is floating when 40 percent of the volume is full.

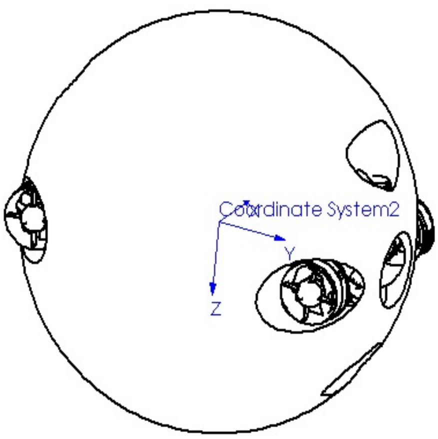

Fig. 1. 3D view of design

B. Thruster configuration

determining the number of degree of freedom for the robot is the keystone in designing process and it directs the complexity of control model. Maneuverability can be formed with regard to the number and configuration of propulsion units and utilizing rudders, stern or heeling in the system. Several models of ROV are introduced in introduction section, as it is described, the most essential DOF for ROV are surge and heave motion.

For this application surge and heave motion beside steering control are considered for the robot. The configuration of the thrusters provide control of robot heading. As it is indicated in the figure 1, there are two manifolds with four openings in each side of the robot. Every manifold contains 2 horizontal and 2 vertical symmetrical thrusters. Note that symmetrical distribution of 8 thrusters are cornerston in our design. Ballast control is considered for long distance heave motion and vertical thruster support the robot for small vertical displacement. Each thruster is $97(D) \times 113(L)$ mm brushless electric motor with maximum power of $34.3N$ in $12v$. Every thruster comes with speed controller unit that is mounted in pressure resistant container and it can be operated via Pulse Width Modulation (PWM). As it will be describe in section III-B it can communicate with embedded PC over $I2C$ protocol.

Simply the produced power by thrusters must be capable of overcoming the drag force while robot is moving horizontally or vertically. For this reason, at the early stage of design it is critical to choose the suitable thrusters in terms of power.

The robot maximum velocity is $0,5m/s$ with water viscosity of $1.6e^{-3}kg/(m.s)$ and calculated Reynolds number of $0.18e^{-6}$. Hence according to [7] following equation the drag would be equal to:

$$F_d = 0.5 \cdot \rho \cdot c_w \cdot V^2 \cdot A = 14.02N \quad (1)$$

Where ρ, c_w and A represent density, drag coefficient and the projected area perpendicular to direction motion.

The horizontal thrusters are placed in an optimize distance in order to produce higher torque while maintaining the streamline robot outline. However, with regard to the weight of robot and the distance between center of gravity and buoyancy, it is infeasible to provide pitch control by the amount of power that thrusters produce.

III. HARDWARE ARCHITECTURE

This section specifies the main electronic components for initial test and driving of robot, however this configuration subject to change in order to improve the vehicle intelligence, as the robot is in initial phase of development.

A. controller

At initial phase of design two controller units considered for the system. The main controller must be capable of running several software modules simultaneously with real-time characteristic and facilitate rapid prototyping . The main controller unit is fanless core i7 dual core 2.5 GH which is equipped with I/O module of 16 sequential analog input and 8 analog output and 16 digital channels. The controller acts as dedicated target computer to run real-time application on hardwares. This embedded controller assigned to the data acquisition from sensors, numerical computation and sending commands to the controller drive. It provides code module for interfaces protocols, therefore developing of control models for every individual components and generating real-time code is not laborious.

The other controller is 8 bit microcontroller unit Atmel (ATmega32HVB) for the system safety power management which can switch the power off in case of leakage or lackage of batteries power to complete the mission.

B. sensor layout for low level control

At very early stage of design number of sensors is considered for the purpose of low level control of the robot. As it is indicated in Fig 2, This section presents the layout of actuators, sensors and their interfaces with main controller briefly. As mentioned before the robot has 8 thrusters which communicate over I2C protocol with controller. Thrusters form a communication network over I2C protocol and each is assigned a unique node ID to be distinguished. Every controller drive can send 9 bytes of data that consist of current status of the motor. Feed back data consists of pulse counter, voltage, temperature, current and ID and it occurs at frequency of 6 HZ.

The robot is equipped with inertial measurement unit (IMU) and Doppler Velocity Log (DVL) to navigate the robot for short displacement in test pool. The depth is measured by pressure sensor which transfer the data through ADC unit over serial communication to the embedded PC. Moreover the leakage and temperature sensors are installed for the safety purposes and in case of emergency they can communicate with MCU in order to power off the electronic bus. Outline of The vision sensor unit which consists of sonar sensor, camera, DVL sensors, are out of scope of this paper

IV. DYNAMIC

As it is indicated in the figure 1 the body frame coordinate system is considered in center of the sphere and x, y and z axes are aligned with surge, sway and heave motion. Furthermore in this section the position and orientation of the robot is calculated in earth fixed frame as inertial coordinate system [8] by applying kinematic transformation matrix.

In principle the center of gravity must be located lower than center of buoyancy in order to passively stabilize the system against pitch or roll momentum. The components inside the robot are distributed equally to place the center of gravity in desire position. It is calculated that the center of buoyancy

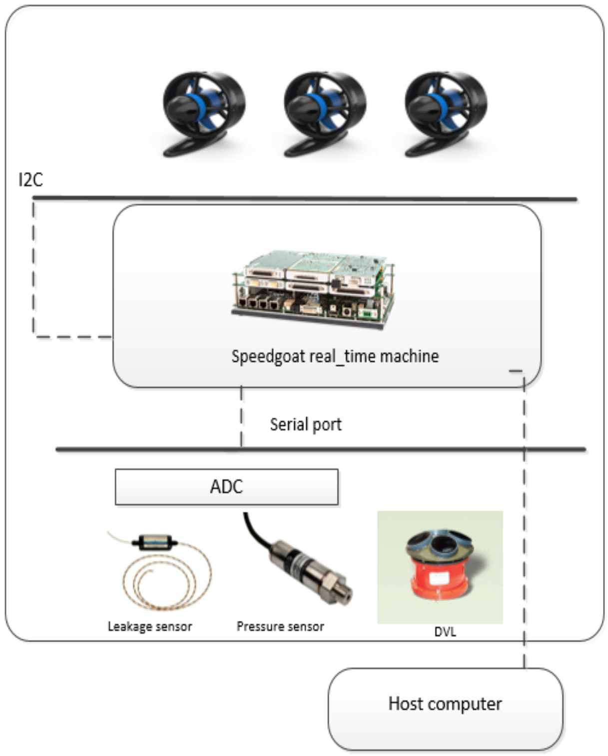

Fig. 2. hardware

and center of gravity are $r_{CB} = [x_{CB}, y_{CB}, z_{CB}] = [0, 0, 0]$ and $r_{CG} = [x_{CG}, y_{CG}, z_{CG}] = [0, 0, 10mm]$ respectively. The equation of motion for a marine vehicle in body frame is as follow:

$$M\dot{V} + C(V)V + D(V)V + g = BT_{thruster} \tag{2}$$

$$\dot{P} = R \cdot V \tag{3}$$

Where V represents six components of linear and angular velocity vector in x,y and z axes of local coordinate system and is indicated by:

$$V = \begin{bmatrix} u \\ v \\ \omega \\ p \\ q \\ r \end{bmatrix} \tag{4}$$

Matrix M represents the inertia matrix. Matrix C represents centripetal and coriolis terms and D represents damping parameters. Buoyancy and gravitational force are represented by g and the external force (thrusters) indicated by matrix $T_{thruster}$. This matrix is a column vector that demonstrates the number of thrusters. Matrix B defines mapping of the thrusters to the corresponding degree of freedom. For simplicity, it is assumed that the motion of the robot take place in an ideal fluid, where there is no significant waves.

Equation (3) is the kinematic transformation in which, matrix P represents the pose of the vehicle in global coordinate system based on Euler angle. Matrix R is 6 by 6 transformation matrix and it consists of rotation matrix R_{xyz} with x,y and z sequence and the inverse of Euler angle rate matrix conjugation.

$$R = \begin{bmatrix} R_{xyz} & 0_{3\times3} \\ 0_{3\times3} & \acute{E}^{-1} \end{bmatrix} \tag{5}$$

According to [9], matrix E maps the Euler angle rate to angular velocity and is equivalent to:

$$E = \begin{bmatrix} Cos\theta \cdot Cos\psi & -Sin\psi & 0 \\ Cos\theta \cdot Sin\psi & Cos\psi & 0 \\ -Sin\theta\psi & 0 & 1 \end{bmatrix} \tag{6}$$

Matrix M is constituted by both rigid body inertia components and added mass components. Since the robot is symmetrical in xz, xy and yz plane, then I_{yz}, I_{yx}, I_{xz} parameters are zero. Hence with regard to center of gravity vector mass $m = 106kg$, the inertia tensor for rigid body is:

$$M_{RB} = \begin{bmatrix} 106 & 0 & 0 & 0 & 1.6 & 0 \\ 0 & 106 & 0 & -1.6 & 0 & 0 \\ 0 & 0 & 106 & 0 & 0 & 0 \\ 0 & -1.6 & 0 & 3.6 & 0 & 0.001 \\ 1.6 & 0 & 0 & 0 & 3.9 & 0 \\ 0 & 0 & 0 & 0.001 & 0 & 3.6 \end{bmatrix} \tag{7}$$

as it is expected, the off diagonal component of the matrix in equation (11) are nearly zero, thus for simplicity of the equation the rigid body mass matrix would be considered as: $Diag\{106\ ,106\ ,106\ ,3.6\ ,3.9\ ,3.6\}$

The added mass matrix is dependent to type of motion and shape of robot and fluid density. For simplicity surge and heave motion of robot decouple from steering dynamic. In the case of a totally submerge vehicle with low speed the off diagonal element of the added mass matrix can be neglected [10] . At this stage there are 3 unknown terms $Z_{\dot{\omega}}$, $X_{\dot{u}}$ and $N_{\dot{u}}$ added mass matrix that must be determined.

For this purpose certain accelerated motion in certain trajectory aligned with degree of freedom can be implemented. However, at early phase of design these components of added mass matrix are calculated based on theoretical relation. The added mass component $Z_{\dot{\omega}}$ for motion of a sphere in an infinite liquid were estimated by [11], which indicate the added mass in x direction when robot has heave motion, this value is equivalent to $56kg$. The same value is achieved for $X_{\dot{u}}$. Moreover, the added mass moment of inertia was estimated by [12] and it is equivalent to $4.07\ kg.m^2$ (This values is proportional to the moment of inertia of fluid displaced by the vehicle's volume)

$$M_a = \begin{bmatrix} X_{\dot{u}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_{\dot{\omega}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & N_{\dot{r}} \end{bmatrix} \tag{8}$$

Matrix C_a is calculated according to components of M_a matrix which has minor effect on equation of motion. Centripetal and Coriolis components of rigid body matrix C_{RB} has small values owing to the fact that robot is spherical and it operates at low velocities. Moreover product of inertia are neglected for calculating the matrix. Hence the C_{RB} would be as following :

$$C_{RB} =$$

$$\begin{matrix} 0 & 0 & 0 & mz_{CG}r & m\omega & -mv \\ 0 & 0 & 0 & -m\omega & mz_{CG}r & mu \\ 0 & 0 & 0 & -m(z_{CG}p-v) & -m(z_{CG}q-u) & 0 \\ -mz_{CG}r & m\omega & -m(z_{CG}p-v) & 0 & I_zr & I_yq \\ m\omega & mz_{CG}r & m(z_{CG}q-\omega) & -I_zr & 0 & I_xr \\ mv & mu & 0 & I_xr & -I_xr & 0 \end{matrix} \tag{9}$$

In order to determine the major components of damping matrix (linear and quadratic parameters), the matrix is assumed diagonal due to the fact that it is running at low speed with no waves in the operating environment. Note that the damping force due to quadratic elements has significantly higher value than linear elements as they are proportional with square of vehicle velocity.

For a completely submerged vehicle with constant velocity in a viscous fluid the main part of hydrodynamic damping is known as drag force. This force is calculated in section II-B, hence the quadratic coefficient ($D_{|v|}\left[N.s^2/m^2\right]$) is derived. The damping coefficient of surge, sway and heave considered to be equal, since the robot is assumed to be symmetrical. On the other hand, the torque due to rotation of sphere is delivered in [13], therefore the linear damping coefficient ($D_{|v|}\left[N.s^2.m/rad\right]$) is determined with regard to maximum $0.7rad/s$ angular velocity of the robot.

$$Diag\{56.52\ u, 56.52\ v, 56.52\ \omega, 0.001, 0.001, 0.001\} \tag{10}$$

Finally the sum of buoyancy and robot's weight expressed in body coordinate system according to their point of action computed as following :

$$g = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 6.8Sin\varphi Cos\theta \\ 10.3Sin\theta \\ 0 \end{bmatrix} \tag{11}$$

B is a mapping matrix to align the external thrusters force with degree of freedom. In our case the B matrix would be as following, which indicated the contribution of thrusters on degree of freedom. Note that first four components of $T_{thruster}$ composed of each two horizontal thrusters on starboard and port while the second four components are vertical thrusters in starboard and port. The r_y and r_z stand for lateral and vertical distance of thrusters from center of gravity, respectively. Note that the torque produced by thrusters is not sufficient to provide pitch or roll angle, as consequence of resistance torque due to distance between center of gravity and buoyancy.

$$B = \begin{bmatrix} 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 \\ 0 & 0 & 0 & 0 & r_y & r_y & -r_y & -r_y \\ -r_z & -r_z & -r_z & -r_z & 0 & 0 & 0 & 0 \\ r_y & r_y & r_y & r_y & 0 & 0 & 0 & 0 \end{bmatrix} \quad (12)$$

At this stage main hydrodynamic parameters that effect on motion of vehicle such as added mass inertia and damping are derived. However, in order to identifies all diagonal and off diagonal parameters such as damping, centripetal and added mass inertia coefficients, certain tests must be implemented. It is critical to determine the type of robot motion in order to estimate the right value of parameters. Usually static tests can be executed to estimate the damping parameters, while the input of the equation (2) is T vector and the velocity of the robot can be determined by DVL (inertial tensor matrix is neglected). Also the accelerated motion can be executed in order to calculate the centripetal and inertia coefficients. In this case input of the equation is vector T and the acceleration must be measured accurately. The static and accelerated motion are according to surge, heave and yaw direction. Note that in order to boost the accuracy of estimated data, every test could be repeated several times. The accuracy of IMU sensors to derive acceleration and velocity also has direct effect on estimation of unknown parameters. The latter verifies the importance of utilizing DVL in underwater robotic application.

V. Conclusion

General architecture design of an underwater robotic vehicle is described. The paper also addresses the hardware layout, communication, protocol interfaces between sensors and embedded PC. Furthermore, The advantage of utilizing a spherical design in low speed due to axial symmetry realizes the feasibility of hydrodynamic parameters estimation at early stage of design.

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