Preliminary concept of a novel spherical underwater robot

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Abstract: This paper describes the preliminary concept of a novel spherical underwater robot (SUR). The novel SUR employs a spherical hull and equipped with multiple vectored water-jet-based thrusters. This paper focuses on the preliminary design of the novel spherical underwater robot’s structure. Based on the structure, the finite element analysis is used to test the strength of structure and the feasibility of the concept. Meanwhile, the simulation of the robot’s dynamics and kinematics is also finished to verify the stabilisation and validity of the new structure. On the basis of the structural characteristics of the spherical robot, its dynamic model is derived by applying the Lagrange-Routh equations briefly. A 3D model of robot is built by CATIA and finite element method is applied base on the model. Then the model is exported to ADAMS for simulation. The results of simulation by combining MATLAB/Simulink with ADAMS are presented. The simulation results indicate that the proposed virtual prototype system has the capability of simulative demonstration and performance validation, and can provide an innovative approach for AUV graphic simulation.

Keywords: spherical underwater robot; SUR; finite element analysis; simulation of kinematics; virtual prototype system; autonomous underwater vehicle; AUV.


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1 Introduction

The spherical underwater robot (SUR) as a member of the new type of spherical robots has made its debut in recent years. It consists of a ball-shaped outer shell to accommodate the whole mechanism inclusive of control devices and energy sources. SUR is characterised as simple, compact, well-sealed structure and agile motion, it has attracted the interest of many researchers. They are believed to have several benefits, such as, locomotion with minimal friction, constrained spaces, omni-directions movement without ever overturning. The spherical structure offers extraordinary motion properties in cases where turning over. These advantages provide the SURs with stronger viability than the traditional autonomous underwater vehicles (AUVs) (Li et al., 2014).

Due to the good water-pressure resistance of spherical objects, spherical robots can perform a rotational motion with a 0° turn radius. Many types of SURs have been developed. ODIN-III was a typical prototype robot developed at the University of Hawaii (Choi and Yuh, 1996; Choi et al., 2003). The SUR was used to monitor the environment and for underwater operations. Researchers at Harbin Engineering University developed a SUR with three water-jet thrusters (Guo et al., 2010a, 2011). However, the propulsive force of the thrusters was considerably reduced because the water input pipeline was curved. In our laboratory, we developed a SUR that used three vectored water-jet thrusters for its propulsion system (Lin et al., 2011; Li and Guo, 2012; Guo et al., 2011; Guo et al., 2010b). The propulsion system was assembled inside the spherical hull to reduce its effects on the robot’s flexibility and to limit damage from possible impacts. But the second-generation spherical underwater robot (SUR-II) which we have made has the problem of high energy consumption. The structure of the propulsion system used in SUR-II is shown in Figure 1. Every thruster has 120° away from each other. This structure has the ability to use the least thrusters (three thrusters) to realise the movement of SUR-II, for instance, the heave, sway, surge, pitch, roll and yaw motion.

In spite of this, there is energy consumption when the robot moving forward. The force analysis of the propulsion system is presented in Figure 2. There are two thrusters provide the propulsive force when the robot moving forward. Through the force analysis, the propulsive force can divide into two opposite component forces which in horizontal and vertical direction. The horizontal component is marked in red, and the vertical component is marked in green. The two horizontal components are synthesised as the main force which drive the robot moving forward, and the two vertical components offset each other to keep the balance. It is the main reason why the three-thruster propulsion system has the high energy consumption.

This paper presents an idea of improved structure of robot to solve this problem. The new structure of the robot takes four vectored water-jet thrusters as its propulsion system. The four-thruster propulsion system is presented in Figure 3. The four-thruster structure has avoided bringing the offset component forces, and reduced energy consumption effectively. And the new structure of the novel SUR has the highly symmetrical characteristic. Obviously, it is useful to equipoise the mass distribution.

The organisation of this paper is as follows. Related work is reviewed in Section 1. Section 2 describes the
preliminary concept in details. Section 3 describes the mathematical modelling and theoretical analysis of the novel SUR. In this section, the trajectory of the SUR is discussed in the quaternion space. The finite element analysis of the novel SUR is inquired in Section 4. The simulation setup along with the discussion on the experimental results is reported in Section 5. Section 6 provides concluding remarks.

Figure 3 Four vectored water-jet thruster propulsion system, (a) blueprint of new propulsion system (b) physical drawing (see online version for colours)

2 Overall design

Our underwater robot is spherical in shape, and equipped with a multiple vectored water-jet-based propulsion system, which differs from previous research. A type of spherical underwater vehicle with traditional blade thrusters was introduced in Do et al. (2004). Watanabe (2006) proposed a spherical AUV with a relatively small size and an externally installed four-blade thruster. In Yue et al. (2013b), the principles and a dynamic analysis of a new type of water-jet thruster were presented, but the system was not used on SURs. The unmanned streamlined underwater vehicle AUV-150, developed by CMERI in India, is propelled by water-jet thrusters.

2.1 Conceptual design of the novel SUR

This research proposes a novel SUR with new structure which has three features: spherical shape, a multiple vectored water-jet-based propulsion system, and totally internal installation. By combining the first two features, motion flexibility could be improved. The novel SUR has an improved propulsion system structure, resulting in better performance compared with the original design. The conceptual design of the SUR is shown in Figure 4. The structural design of the novel SUR was symmetric about the Z-axis. Its total diameter was 40 cm.

There are four vectored water-jets which fixed on a waterproof box, as shown in Figure 4(a). The four water-jets are well-distributed on the circumference; every water-jet is 90° away from each other. The inside of the robot is shown in Figure 4(b). The vectored water-jet-based propulsion system can take back to the robot when the robot is out of operation, which can avoid the damage of the robot. Even the robot is under working, the propulsion system structure can also reduce the resistance, which is totally different from other structures. As the water-jet just has a little protruding beyond the surface of the robot when it is working. The mode of motions will be introduced in 2.3.

2.2 Concept of the mechanical structure

This paper focus on how motion performance will be affected by using a vectored water-jet-based propulsion system on a SUR. The essential mechanical components of the novel SUR is shown in Figure 5. The physical picture of the robot is presented in Figure 6.

Waterproofing is critical for underwater applications. Since the hull was not waterproofed, we required a waterproof box for electronic components. All the non-watertight parts of the robot, such as the controller, circuit, batteries and sensors can be sealed in the waterproof box. The box is made of acrylic. Its total height was 22 cm and its inner diameter was 14 cm. The four vectored water-jets comprise the whole propulsion system.

Figure 4 Overall structure of the novel SUR, (a) conceptual design (b) inside view (see online version for colours)

The physical view of the propulsion subsystem is presented in Figure 7. And we have realised the whole propulsion subsystem, the relationship between duty cycles and turning angles is shown in Figure 8.

Figure 8(a) presents the initial position when the thruster is at 0°. We can see that the indication of the signal generator is 5.9%. Meanwhile, Figure 8 (b) shows the thruster is at 90°, and the indication of the signal generator is 10.4%. That means, when the servo motor turns from 0° to 90°, the changes in the value of the signal generator’s indication is 4.5%. So we can get the relationship between
duty cycles and turning angles: $1^\circ$ change of the turning angle corresponds the 0.05% change of the duty cycle.

**Figure 5** Mechanical structure of the robot (see online version for colours)

**Figure 6** Four vectored water-jet thruster propulsion system, (a) front view (b) vertical view (see online version for colours)

**Figure 7** The structure of the propulsion subsystem (see online version for colours)

**Figure 8** The relationship between duty cycles and turning angles, (a) the thruster at $0^\circ$ (b) the thruster at $90^\circ$ (see online version for colours)

2.3 Motion states of the novel SUR

Refer to the content in the previous section, there are eight servos and four thrusters should be controlled to realise the movements of the SUR. The control strategy is presented in Figure 9.

**Figure 9** Flow chart of the control strategy

The three main degrees of freedom were analysed in detail: forward, circumgyrate, and sinking. In general, two water-jet thrusters are employed to provide propulsive force for forward motion and the other two thrusters can be used as the steering device. With the new structure of the propulsion system, more powerful propulsive force is generated by just two thrusters without the counteraction of component force. If high speeds are required, the angle of the propulsive force can be adjusted by servomotors, and four water-jet thrusters are employed to provide propulsive force for forward motion, as shown in Figure 10.

The circumgyrate motion is shown in Figure 11. At this motion, four water-jet thrusters are employed to provide force for gyrating. The rotational angle can be measured by using the feedback from a gyroscope.

**Figure 10** The forward motion and full speed ahead motion, (a) forward motion (b) full speed (see online version for colours)
The sinking and floating motion is shown in the Figure 12. At this motion, the four water-jet thrusters also are employed to provide force for floating and sinking. With the incremental thruster, the robot can realise the demanding motion neatly, which is almost impossible for the previous design with the three thrusters.

The potential application field of the proposed robot is the fixed point 360° intelligent investigation in underwater environment. With the flexibility of the four-thruster structure and the reasonable mass distribution, the novel SUR can realise the omni-directional motion to investigate the surrounding environment, which is almost impossible for the previous robot. Based on the potential application fields of the proposed robot, it should be difficult to detect when the robot is on the latency mission. With the new distribution of the thrusters, the exerted part of the propulsive system can be almost totally concealed in the hull of the novel SUR. The process can realised through the driving of the servo motor. And the latency state robot has a complete spherical shape to dodge the detection of the sonar. As it is shown in Figure 13.

Based on the presented weight distribution, it is difficult to realise the full speed motion. There are two experiments have been carried out to try to solve this problem. To change the weight distribution, the barycentre should be regulated accurately. Two approached of changing the barycentre are proposed. Firstly, a mess block which is fixed on the hull with springs is used to change the weight distribution when the robot turning angles. Figure 14 shows the concept of the mechanism. Figure 15 presents experimental prototype of the mechanism.

As the effect of the inertia, the barycentre of robot will be change quickly with the spin of the SUR. The results
verified the feasibility of this approach. However, it is hard to control the process of changing. A relatively high frequency is required for this mechanism to work. The sway frequency of the underwater vehicle may be not enough for the stabilisation mechanism. Hence, another method is tested to do the work.

Figure 16 shows the second approach to realise the adjustment of the weight distribution. Four mass blocks are used to regulate the barycentre of robot. Each block can be controlled to move through the threaded rod. The second type of the mechanism has more sensitive to motion frequency. Anyway, further work will focus on the stability and feasibility of changing the barycentre with quick response.

3 Theoretical analyses of the novel SUR

This section describes the development of an analytical model of the novel SUR using quaternion.

3.1 Mathematical modelling

3.1.1 Establishment of coordinated system

Since the novel SUR has a symmetrical characteristic structure, the model is founded in one plane. OXY plane is chosen to be the reference plane. Other situation can be deduced from the proposed analysis. Considering a spherical robot on a horizontal plane as shown in Figure 17, an inertial coordinate frame is attached to the ground and denoted as XYZ with its origin at the point O.

Figure 17 Coordinates setup of the novel SUR (see online version for colours)

The body coordinate axes Xs, Ys, Zs, parallel to XYZ, are attached to the sphere and have their origin at the centre of the sphere Os. The set of generalised coordinates describing the sphere consists of:

1. coordinates of the contact point Oc on the plane
2. any set of variables describing the orientation of the sphere (Das and Mukherjee, 2004, 2006; Bruhna et al., 2008; Gilyén and Szvoboda, 2009).

The Euler parameters (instead of Euler angles) which are a set of four parameters are used to describe the orientation of the sphere. Euler parameters have the advantage of being a non-singular two to one mapping with the rotation. In addition, Euler parameters form a unit quaternion and can be manipulated using quaternion algebra (Yue et al., 2012, 2013a).

3.1.2 Mathematical model of the novel SUR

X and Z are the coordinates of the contact point Oc between the sphere and the plane, and (α, β, γ) are the generalised Euler angles used to describe the sphere orientation. We have adopted a Newton formulation for propulsion mechanism since the acceleration of the sphere appears explicitly in the equation. These equations have the form:

\[ \sum \vec{M} = (\sum \{I\}) \cdot \vec{\omega} + \sum \vec{r} \times \vec{m} \cdot \vec{\rho} \quad (1) \]

where \( \sum \{I\} \) is the moment due to the weights of the individual masses, \( I \) is the moment of inertia of the robot and \( \vec{\omega} \) is the angular acceleration of the sphere robot. The vector \( \vec{\rho} \) represents the position vector of the robot. The vectors represented by \( \vec{\rho} \) are equivalent to the absolute accelerations of individual parts.

In our implementation, due to discrete nature of the server motors, we can suppose, for each step of simulation, each is temporarily fixed in its position related to the geometry. Thus, we can neglect the second term on the right hand of the equation in a good rate of approximation. It helps calculating angular acceleration. A static analysis has the following form:

\[ \sum \vec{M} = (\sum \{I\}) \cdot \vec{\omega} \quad (2) \]

let \( i, j, k \) be the unit vectors of the body frame and \( \vec{\omega} \) be the angular velocity of the sphere given by

\[ \vec{\omega} = (\alpha c \beta \gamma + \beta s \gamma) i + (-\alpha c \beta s \gamma + \beta c \gamma) j + (\alpha s \beta + \gamma) k \quad (3) \]

where \( c \beta \) and \( s \beta \) are short for \( \cos \beta \) and \( \sin \beta \), respectively. Let \( \xi, \eta, \zeta \) be the unit vectors of inertial coordinate frame, and the projection of the angular velocity vector on the body axes can be derived and expressed in the following form.

\[ \omega = \omega_i + \omega_j + \omega_k = (\alpha + \gamma s \beta) \xi + (\beta c \alpha - \gamma s a c \beta) \eta + (\beta s \alpha + \gamma c a c \beta) \zeta \quad (4) \]

Let us suppose that the robot rolls without slipping. Hence, the velocity of the contact point Oc, with respect to the inertial coordinates is zero. The constraint equations reduce to

\[ \vec{v}_i = \dot{x} + \omega_j \cdot r = \dot{x} + (\beta s \alpha + \gamma c a c \beta) r \quad (5) \]

\[ \vec{v}_k = \dot{z} - \omega_j \cdot r = \dot{z} - (\alpha + \gamma s \beta) \cdot r \quad (6) \]

where \( r \) is distance vector.
Due to the symmetric design of the ball, the gravity force acts vertically through the centre of the spherical robot and the contact point \( O_c \). Both the reaction force and frictional force act through the \( O_c \) contact point. Hence, the sum of the external moment at the contact point \( O_c \) is zero. And the angular moment of the robot at \( O_c \) is a conservative quantity. Therefore, the resultant moment vector is as following.

\[
\vec{M} = mg \begin{bmatrix} z1 + z2 + z3 + z4 \\ -x1 - x2 - x3 - x4 \end{bmatrix}
\]  

(7)

### 3.2 Trajectory planning

Because of omni-directional property of the robot, direct path is proposed and the travelling path is very close to the shortest path to the target. For calculating the moment of inertia, we use three \( 3 \times 3 \) matrixes as below:

\[
I^r = \begin{bmatrix} I_{xx}^r & I_{xy}^r & I_{xz}^r \\ I_{yx}^r & I_{yy}^r & I_{yz}^r \\ I_{zx}^r & I_{zy}^r & I_{zz}^r \end{bmatrix},
I^t = \begin{bmatrix} I_{xx}^t & I_{xy}^t & I_{xz}^t \\ I_{yx}^t & I_{yy}^t & I_{yz}^t \\ I_{zx}^t & I_{zy}^t & I_{zz}^t \end{bmatrix},
F = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}
\]  

(8)

where \( I^r \) and \( I^t \) are the moment vector caused by the motor, the propulsion system and the spherical shell respectively, and \( \vec{F} \) are both constant. In equation (8), \( I_{xx}^r \) and \( I_{xy}^r \) are as follows:

\[
I_{xx}^r = T_{xx}^r + mdx^2,
I_{xy}^r = T_{xy}^r + mdy^2,
I_{xz}^r = T_{xz}^r + mdz^2
\]  

(9)

Equation (9) is transfer-of-axis relations for transferring \( \vec{T} \) from the centre to \( O_c \). Also, in equation (9), due to symmetrical design of the robot \( I_{xy} = I_{yx} \) and the other parameters are calculated likewise.

Let \( X \), \( Y \) and \( Z \) be the projection of the propulsive force on the body coordinate axes be the velocity of the sphere, the relational equation can be expressed by

\[
\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \prod_{k=1}^{n} A_k \\ 0 \\ -mg \\ 0 \end{bmatrix}
\]  

(10)

In equation (10), the elements of the ration matrix \( A_k \) is given by

\[
A_k = \begin{bmatrix} c\beta_k c\gamma_k & c\alpha_k s\gamma_k + s\alpha_k c\beta_k c\gamma_k & s\alpha_k c\gamma_k - c\alpha_k s\beta_k c\gamma_k \\ -c\beta_k c\gamma_k & c\alpha_k s\gamma_k - s\alpha_k c\beta_k c\gamma_k & s\alpha_k c\gamma_k + c\alpha_k s\beta_k c\gamma_k \\ s\beta_k & -s\alpha_k c\beta_k & c\alpha_k c\beta_k \end{bmatrix}
\]  

(11)

Let us suppose that \( \epsilon^x_n \), \( \epsilon^y_n \) and \( \epsilon^z_n \) are the projection of the angular velocity of the sphere in the \( (n - 1) \)th step, given by

\[
\begin{bmatrix} \epsilon^x_n \\ \epsilon^y_n \\ \epsilon^z_n \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\]  

(12)

from equation (8), equation (10) and equation (12) the resultant moment equation in the \( n \)th step is as following

\[
\begin{bmatrix} Z \sum_{k=1}^{n} y_{k-n} - Y \sum_{k=1}^{n} z_{k-n} \\ X \sum_{k=1}^{n} z_{k-n} - Z \sum_{k=1}^{n} x_{k-n} \\ Y \sum_{k=1}^{n} x_{k-n} - X \sum_{k=1}^{n} y_{k-n} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\]  

(13)

Therefore, by equation (5), equation (6) and equation (13), the next position can be calculated as below:

\[
\begin{bmatrix} x_n + \left( \beta_n s\alpha_n + \gamma c\alpha_n c\beta_n \right) r = 0 \\ y_n - \left( \alpha_n + s\alpha_n + \gamma c\alpha_n c\beta_n \right) r = 0 \end{bmatrix}
\]  

(14)

### 4. Finite element analysis of the novel SUR

To test the structural strength and the feasibility of the novel SUR concept, the finite element method is applied. FEM is widely used in engineering field for complex structural simulation due to its capability to allow detailed visualisation of where structures bend or twist, and indicate the distribution of stresses and displacements (Kmet et al., 2013; Pu and Yang, 2013). The analysis procedure is illustrated in Figure 18.

The FEM include two parts: the preprocessing and the post processing. The preprocessing contains mesh generation, restraints and loads definition. The post
processing is comprised of the calculation and analytic result (Bondy et al., 2014). The novel SUR will be analysed according to the procedure. Firstly, the whole robot should be divided into many elements, which is the essence of the FEM. The mesh generation of the SUR is shown in Figure 19. The robot is divided into 62,799 nodes and 213,418 elements.

Figure 18  Analysis procedure of the finite element method

Secondly, define the restraints and the loads, as is presented in Figure 20. Several procedural parameters are defined in turn. For instance, definition of the smooth spring virtual parts, ball joints, sliding pivot, pressure, distributed force, bearing load and force density.

Finally, we can carry on a calculation and check the results which are displayed in Von Mises and other isoboles. Figure 21 presents the results of the post processing. The pressure on the surface of the SUR is 1,000 N, which simulates the robot is in the 2 m depth under water. We can easily find that the structural strength meets the qualification, and the stress concentration points are distributed in the hatch of the hull, this part should be disposed specially.

Figure 20  Define the restraints and the loads (see online version for colours)

Figure 21  Results of the post processing, (a) Von Mises stress (b) deformation (c) principal stress (d) precision (see online version for colours)
5 Simulation and results

The ADMAS is used to carry on the kinetic simulation of the novel SUR. ADAMS is the most widely used multi-body dynamics and motion analysis software in the world. Traditional ‘build and test’ design methods are now too expensive, too time consuming, and sometimes even impossible to do. ADAMS multi-body dynamics software enables engineers to easily create and test virtual prototypes of mechanical systems in a fraction of the time and cost required for physical build and test. Unlike most CAD embedded tools, ADAMS incorporates real physics by simultaneously solving equations for kinematics, static, quasi-static, and dynamics.

Table 1 Parameters of simulation model

<table>
<thead>
<tr>
<th>Parameters names</th>
<th>Numerical value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>The length of the nozzle (thruster)</td>
<td>60</td>
<td>mm</td>
</tr>
<tr>
<td>The diameter of the nozzle (thruster)</td>
<td>14</td>
<td>mm</td>
</tr>
<tr>
<td>Height of the waterproof box (internal diameter)</td>
<td>140</td>
<td>mm</td>
</tr>
<tr>
<td>Height of the waterproof box (external diameter)</td>
<td>220</td>
<td>mm</td>
</tr>
<tr>
<td>Weight of motor (each)</td>
<td>732</td>
<td>g</td>
</tr>
<tr>
<td>Radius of spherical shell</td>
<td>200</td>
<td>mm</td>
</tr>
<tr>
<td>Weight of spherical shell</td>
<td>800</td>
<td>g</td>
</tr>
</tbody>
</table>

Due of 3D solid modelling ability of ADAMS is not very strong, the CATIA software is employed to setup the 3D model, and then export to ADAMS2007 for simulation, the model is shown in Figure 22. Also, because the ADAMS’ controllers are not ones for professional modelling tool, so its control capabilities are limited, however, interfaces between ADAMS and other software such as MATLAB, EASY and so on allow ADAMS complete fine system simulation.

Figure 22 3D model of the novel SUR in CATIA (see online version for colours)

In this section, simulation results on the spherical robot by ADAMS using a time step 0.01 s are presented to demonstrate the effectiveness of the design and verify the path following performance. The system parameters are given in Table 1, and the experiment results are shown in Figure 23 and Figure 24.

Figure 23 The trajectories of the novel SUR on the x-z plane (see online version for colours)
Figure 24  Simulation results for the novel SUR, (a) variation in X-axis (b) variation in Z-axis (see online version for colours)
The results of the SUR in tracking a straight line in x-z plane is shown in Figure 23, in contrast with reference line (red). As expected, simulations reveal that the spherical robot converges globally uniformly to the desired point with acceptable dynamic performances.

The evolutions of the variables for tracking the desired curve are shown in Figures 24(a) and 24(b). The reference linear velocity \( v_l \) is 100 mm/s. Figures 24(a) and 24(b) indicate that the robot starts in the x-z plane at \( t = 0.75 \) s. This corresponds to a pure moving motion. Simulation indicates that the velocities generated oscillatory and chattering behaviour with these assumptions.

6 Conclusions

A mathematical model of novel SUR motion was established using the conservation of angular momentum, and an algorithmic motion planning was developed. The model was validated through a set of simulations. Results of simulations and experimental trajectories of the robot on the plane were found consistent with a reasonable accuracy and the methods are effective. Comparing with existing motion plans, most of which require intensive numerical calculations, strategies in this paper involve simple algorithmic iteration and provide the scope for easy implementation. However, experiments also show that the SUR has a strong tendency to oscillate. So a robust closed-loop controller and suitable stabilisation method are necessary. Study in this paper demonstrates the feasibility of the approaches and a better controlled SUR is expected to be improved in the future. On the basis of the analytic results mentioned, the concept is feasible and valid. Our team will manufacture a prototype based on the concept.

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