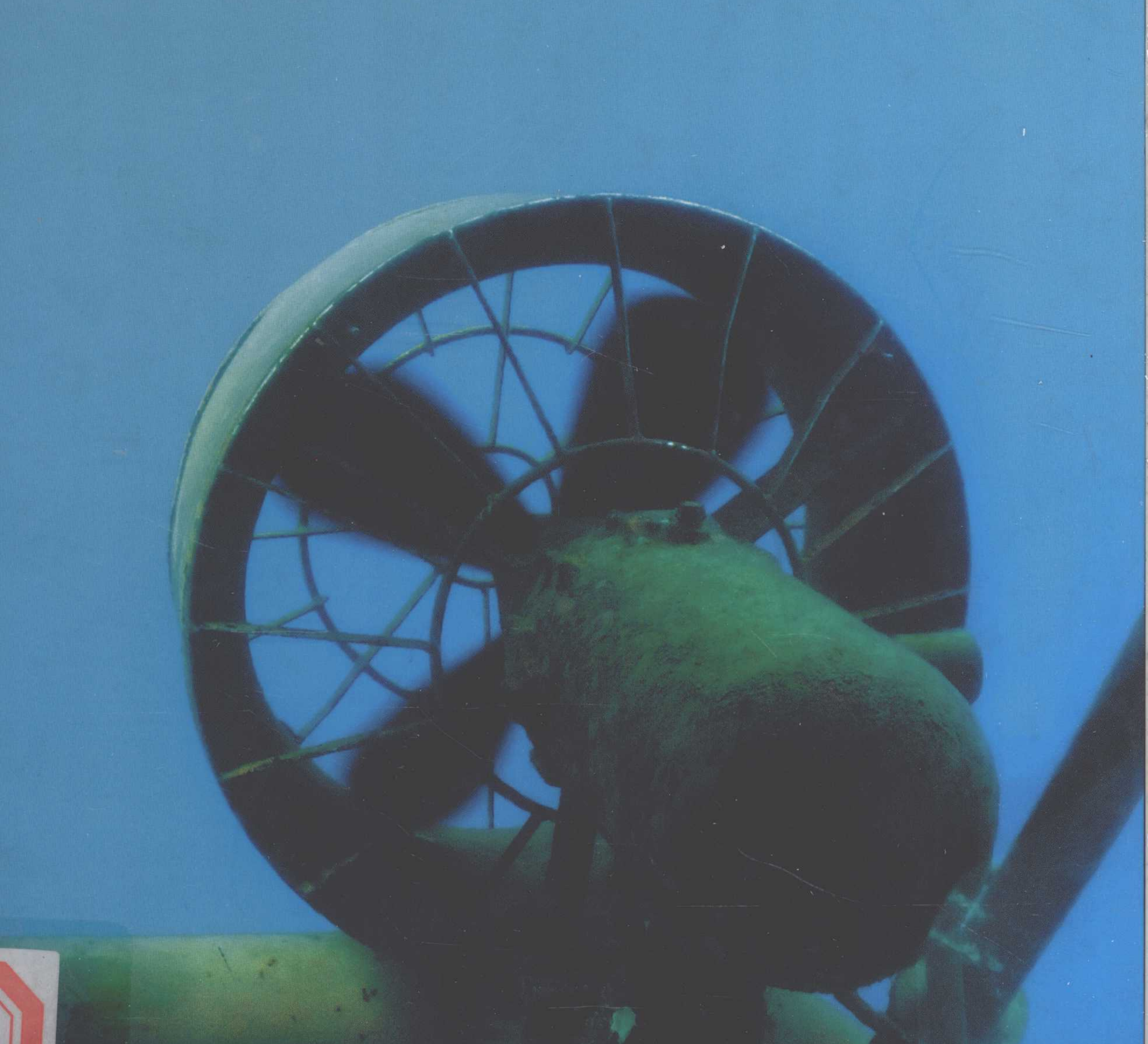
AUTONOMOUS UNDERWATER VEHICLES

Edited by **Nuno A. Cruz**



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Preface

Autonomous Underwater Vehicles (AUVs) are remarkable machines that revolutionized the process of gathering ocean data. Their major breakthroughs resulted from successful developments of complementary technologies to overcome the challenges associated with autonomous operation in harsh environments. This book brings together the work of many experts in several domains related to the design, development and deployment of AUVs.

During the last decades, AUVs have gone through notable developments. In the late eighties and early nineties, the first prototypes required a tremendous effort and ingenious engineering solutions to compensate for the technological limitations in terms of computational power, batteries, and navigation sensors. To deploy these expensive vehicles navigating autonomously in a very unforgiving environment, and expecting them to return safely was a true act of faith in engineering, a scaled version of the early efforts in space technology.

The initial developments continued steadily and, by the end of the last century, AUVs have gradually moved from the controlled academic environment into challenging operational scenarios, covering scientific, commercial and military applications. As the technology matured, many different solutions were effectively demonstrated, in various sizes and configurations, and a few evolved into commercial products.

Underwater robotics is a peculiar field of knowledge, bringing together specific complementary knowledge in mechanical and electrical engineering, and also in computer science. In the last decade, with the impressive improvements in computational power, battery technology, and miniaturization of electronic systems, AUVs became less cumbersome and more amenable to be used as test beds for new techniques for data processing. As smaller, lighter, and less expensive equipment became available, the access to operational vehicles was further facilitated and more and more prototypes became accessible for testing new algorithms and solutions. The geographic span of valuable scientific work with field results was extended to include a larger number of researchers, not only from leading scientific institutions but also from more modest laboratories in emerging countries. This has resulted in an exponential increase in AUV development and deployment, alone or in fleets, with arguably many thousands of hours of operations accumulated around the world, and corresponding amount of data. Autonomous Underwater Vehicles became a common tool for all communities involved in ocean sampling, and are now a mandatory asset for gathering detailed ocean data at very reasonable costs.

Most of the advances in AUV capabilities aimed at reaching new application scenarios and decreasing the cost of ocean data collection, by reducing ship time and automating the process of data gathering with accurate geo location. Although this yielded significant improvements in efficiency, new approaches were also envisaged for a more productive utilization of this new tool. With the present capabilities, some novel paradigms are already being employed to further exploit the on board intelligence, by making decisions on line based on real time interpretation of sensor data. In many organizations, this ability is also being applied to allow the AUVs to conduct simple intervention tasks.

The design of Autonomous Underwater Vehicles is governed by a complex tradeoff between the critical requirements of the planned missions, and the main constraints on fabrication, assembly and operational logistics. Contrary to the early tendency to develop general purpose vehicles, the current pursuit of efficiency has pushed the concept of specific vehicles for specific tasks, frequently taking advantage of modular designs to accelerate the assembly time.

In the last years, there have been a great number of publications related to underwater robotics, not only in traditional engineering publications, but also in other fields where the robotic solutions are being used as a tool to validate scientific knowledge. There are also numerous conferences held each year, addressing all aspects of AUV development and usage. Both have served to report the major breakthroughs and constitute a foremost source of reference literature. This book collects a set of self contained chapters, covering different aspects of AUV technology and applications in more detail than is commonly found in journal and conference papers. The progress conveyed in these chapters is inspiring, providing glimpses into what might be the future for vehicle technology and applications.

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Part 1

Vehicle Design

1

Development of a Vectored Water-Jet-Based Spherical Underwater Vehicle

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Japan

1. Introduction

The applications of underwater vehicles have shown a dramatic increase in recent years, such as, mines clearing operation, feature tracking, cable or pipeline tracking and deep ocean exploration. According to different applications, the mechanical and electrical configuration and shape of an underwater vehicle are different. For instance, manipulators are necessary when doing mines clearing operation or some other tasks which need to deal with environment. If an underwater vehicle is used for underwater environment detection or observation, it is better to make this vehicle smaller and flexible in motion that it can go to smaller space easily. If the vehicle needs high speed moving in the water then a streamline body is required.

Different structures with different size of underwater vehicles are developed. Most of these underwater vehicles are torpedo-like with streamline bodies, like (Sangekar et al., 2009). And there are some small size AUVs like (Allen et al., 2002) and (Madhan et al., 2006). And also there are some other AUVs adopt different body shape, such as (Antonelli & Chiaverini, 2002). Meanwhile, the propulsion system is one of the critical facts for the performance of underwater vehicles, because it is the basis of control layers of the whole system. Propulsion devices have variable forms, for instance, paddle wheel, poles, magneto hydrodynamic drive, sails and oars.

Paddle wheel thrusters are the most common and traditional propulsion methods for underwater vehicles. Usually, there are at least two thrusters installed on one underwater vehicle, one for horizontal motion and the other for vertical motion. The disadvantages of paddle wheel thrusters are obvious, for example, it is easy to disturb the water around the underwater vehicles. Meanwhile, the more the paddle wheel thrusters are used, the weight, noise and energy consumption increases.

The steering strategies of traditional underwater vehicles are changing the angular of rudders or using differential propulsive forces of two or more than two thrusters. Of course, there are vectored propellers being used on underwater vehicles. Reference (Cavallo et al., 2004) and (Le Page & Holappa, 2002a) present underwater vehicles with vectored thrusters. Reference (Duchemin et al., 2007) proposes multi-channel hall-effect thrusters which involves vector propel and vector composition. Reference (Le Page & Holappa, 2002b) proposes an autonomous underwater vehicle equipped with a vectored thruster. At the same time, the design of vectoring thrusters used on aircrafts is also an example of vectored propulsion system (Kowal, 2002), (Beal, 2004) and (Lazic & Ristanovic, 2007).

The purpose of this research is to develop such a kind of underwater vehicle which can adjust its attitude freely by changing the direction of propulsive forces. Meanwhile, we would like to make the vehicle flexible when moving in the water. Inspired by jet aircraft, we adopt vectored water-jet propellers as the propulsion system. According to the design purpose, a symmetrical structure would be better for our underwater vehicle (Guo et al., 2009).

This spherical underwater vehicle has many implementation fields. Because of its flexibility, our vehicle can be used for underwater creatures observation. For example, we can install underwater cameras on the vehicle. It can track and take photos of fishes. Another example is that, due to its small size, we can use it to detect the inside situation of underwater oil pipes.

2. Mechanical and electrical design

2.1 Mechanical system design

Before the practical manufacture, we try to give a conceptual design of the whole structure for this spherical underwater vehicle. At this stage, we need to consider about the dimension, weight distribution, material, components installation, and so on. And we also need to consider about the configuration of the propulsion system, for example, how many water-jet propellers should we use for the purpose of optimizing power consumption without decreasing propulsion ability. Therefore, by all of that mentioned above, we give the conceptual designed structure of our spherical underwater vehicle as shown in Fig.1.

It adopts a spherical shape, all the components are installed inside the body. Its radius is $20cm$ which is smaller than that in (Antonelli et al., 2002). Its overall weight is about $6.5kg$. Its working depth is designed to 0 $10m$, with a max speed of about $1.5m/s$.

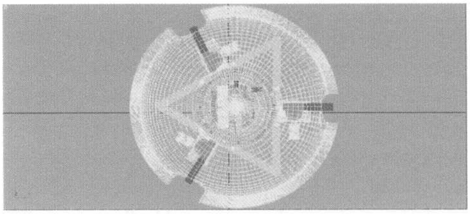
Inside the vehicle, there will be three water-jet propellers used as propulsion system, which is enough for surge, yaw and heave. One waterproof box is used for all the electronic components such as sensors, batteries and the control boards. And all of these are mounted on a triangle support which is fixed on the spherical hull. The whole structure is symmetrical in z-axis. Therefore, it can rotate along z-axis, and by doing this, the vehicle can change its orientation easily.

2.1.1 The spherical hull

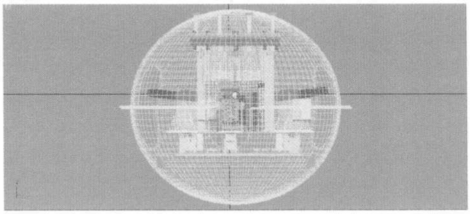
As shown in Fig.2, the spherical hull of this underwater vehicle is made of acrylic which is light and easy to be cut. It is about $3mm$ thick and the diameter is $40cm$. Actually, we can see that this spherical hull is composed of two transparent hemisphere shells. There are three holes which can provide enough space for water-jet propellers to rotate for different motions. We will discuss the details about the principles of the water-jet propulsion system in the next section.

2.1.2 The waterproof box

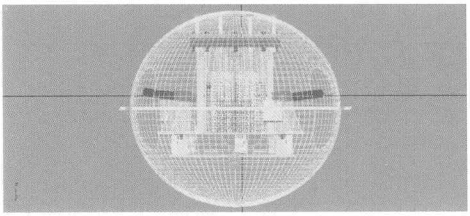
Waterproof is essential for underwater vehicles. Fig.3 shows the design of the waterproof box. The whole size of this box is about $22cm$(hight) $\times$ $14cm$(inner diameter). An O-ring is used for seal, which has the ability to provide waterproof in our case. Inside the waterproof box, there will be two control boards, one or two lithium batteries, depending on tasks. Meanwhile, at the top part inside the box, there will be an digital rate gyro sensor for orientation feedback. The body of waterproof box is also transparent, therefore, we can easily observe the inside working status .



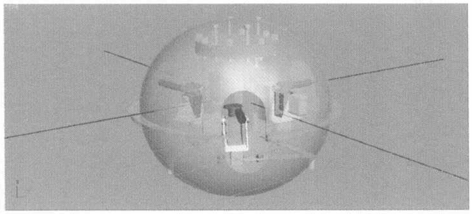
(a) Top View



(b) Front View

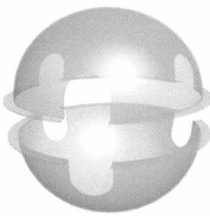


(c) Side View

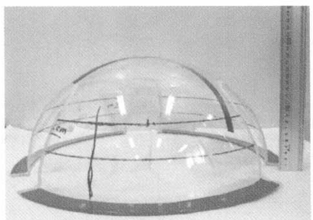


(d) Computer Rendering

Fig. 1. Mechanical System Schematics of the Spherical Underwater Vehicle

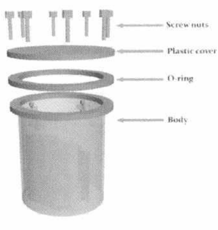


(a) Design

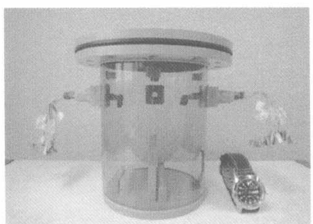


(b) Prototype

Fig. 2. Spherical Hull



(a) Design

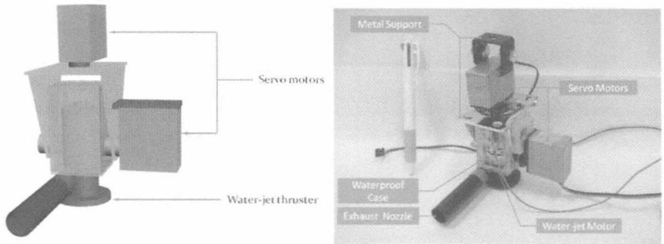


(b) Prototype

Fig. 3. Design of Waterproof Box

2.1.3 Mechanism of the water-jet propulsion system

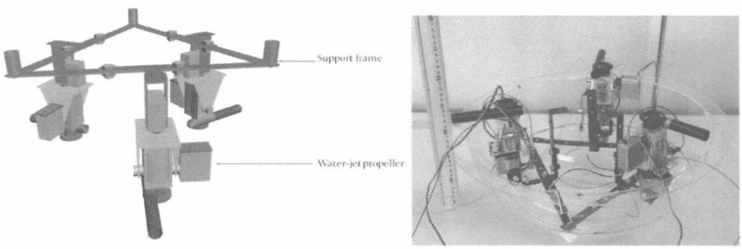
Fig.4 is the structure of one single water-jet propeller. It is composed of one water-jet thruster and two servo motors (above and side). The water-jet thruster is sealed inside a plastic box for waterproof. And we use waterproof glue on servo motors for waterproof. The thruster can be rotated by these two servo motors, therefore, the direction of jetted water can be changed in X-Y plane and X-Z plane, respectively.



(a) Design (b) Prototype

Fig. 4. Structure of a Water-jet Propeller

Three of the water-jet propellers are mounted on the metal support frame, as shown in Fig.5. Three of them are circumferentially $2\pi/3$ apart from each other.



(a) Design (b) Prototype

Fig. 5. Water-jet Propellers mounted on Support Frame

2.2 Electrical system design

We adopt a minimal hardware configuration for the experimental prototype vehicle. For a single spherical underwater vehicle, there are three major electrical groups, sensor group, control group and actuator group. Fig.6 gives the electrical schematics. At present, we only use one pressure sensor for depth control and one gyro sensor for surge control. One ARM7 based control board is used as central control, data acquisition, algorithm implement and making strategic decisions. One AVR based board is used as the coprocessor unit for motor control. It receives the commands from ARM and translates the commands into driving signals for the water-jet propellers.

Fig.7 gives the main hardware for this vehicle. Fig.7(a) is the ARM7 based board with S3C44B0X on it, which can fulfill our requirement at present. Fig.7(b) is the AVR based board with ATmega2560 on it. RS232 bus is used for the communication between ARM7 and AVR. In Fig.7(c) is the set of pressure sensor with the sensor body(right) and its coder (left). It use RS422 bus for data transmission. Digital gyro sensor CRS10 is shown in Fig.7(d), we use the build in AD converter of S3C44B0X for data acquisition.

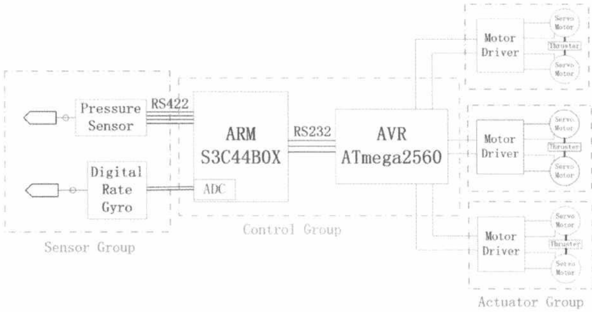
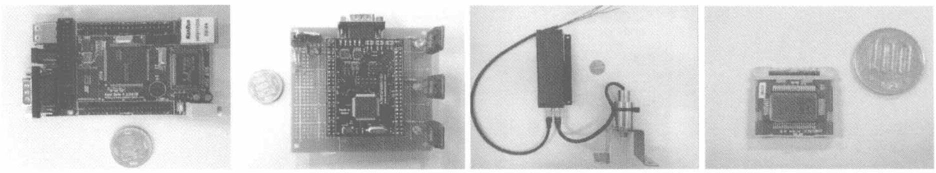


Fig. 6. Electrical Schematics for Prototype System



(a) S3C44B0X Board (b) ATmega2560 Board (c) Pressure Sensor (d) Gyro Sensor

Fig. 7. Electrical Components for the Experimental Prototype Underwater Vehicle

2.3 Power supply

We adopt two power supply for the spherical underwater vehicle. The highest power consumption components in our vehicle are propellers. For each of them, the thruster has a working voltage of $7.2V$ and $3.5A$ current drain, servo motors can work under $5V$ with relatively small current. Therefore, we use two 2-cells LiPo batteries as the power supply for the propellers. The capacity of each battery is $5000mAh$ with parameter of $50c - 7.4V$. Besides, we use 4 AA rechargeable batteries for the control boards. We carried out the power consumption test for one LiPo battery, and Fig.8 gives the battery discharge graph of the power system.

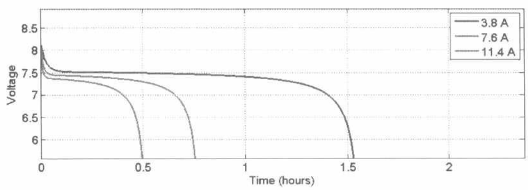


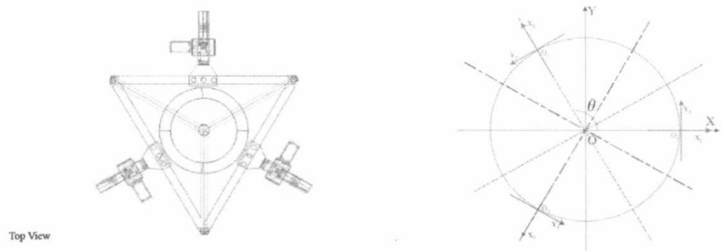
Fig. 8. Power Consumption of the Whole System. Blue line – one propeller working; green line – two propellers working; red line – three propellers working

3. Principles and modeling of the propulsion system

In this section, we will discuss about the working principles, modeling method and the identification experiment for the water-jet propeller. Many literatures have presented the computing formula for the torque and thrust exerted by a thruster. Most of them are base on the lift theory, and mainly focus on blades type propellers (Newman, 1977), (Fossen, 1995) and (Blanke et al., 2000). Our propellers are different with blades type propellers, therefore, we try to find another method for the modeling of water-jet propellers. In (Kim & Chung, 2006), the author presented a dynamic modeling method in which the flow velocity and incoming angle are taken into account. We will use this modeling method for our water-jet propellers.

3.1 Working principles

Before modeling of propulsion system, we want to give some basic working principles about the water-jet propellers. Fig.9(a) shows the top view of distribution of three propellers. They can work together to realize different motion, such as surge and yaw.



(a) Propeller Distribution (b) propeller-fixed Coordinates

Fig. 9. Distribution and Coordination of Multiple Propellers

If we let θ be the interval angle of each water-jet propeller, as shown in Fig.9(b), then, for the purpose of kinematics transform, three propeller-fixed coordinates are introduced for propellers, which are fixed in the rotation center of the propellers. So we can see, these three propeller-fixed coordinates are actually transform results of vehicle-fixed coordinate reference frame. Meanwhile, it should be noted that, this transform only happens in X-Y plane. Let the matrix form of the coordinates transform be given as:

$$\begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} + \begin{pmatrix} -R \\ 0 \\ 0 \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} X_2 \\ Y_2 \\ Z_2 \end{pmatrix} = \begin{pmatrix} c\theta & s\theta & 0 \\ -s\theta & c\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} + \begin{pmatrix} \frac{1}{2}Rc\theta - Rs\theta c\frac{\pi}{6} \\ -\frac{1}{2}Rc\theta - Rc\theta c\frac{\pi}{6} \\ 0 \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} X_3 \\ Y_3 \\ Z_3 \end{pmatrix} = \begin{pmatrix} c2\theta & s2\theta & 0 \\ -s2\theta & c2\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} + \begin{pmatrix} \frac{1}{2}Rc2\theta + Rs2\theta c\frac{\pi}{6} \\ -\frac{1}{2}Rc2\theta + Rc2\theta c\frac{\pi}{6} \\ 0 \end{pmatrix} \tag{3}$$

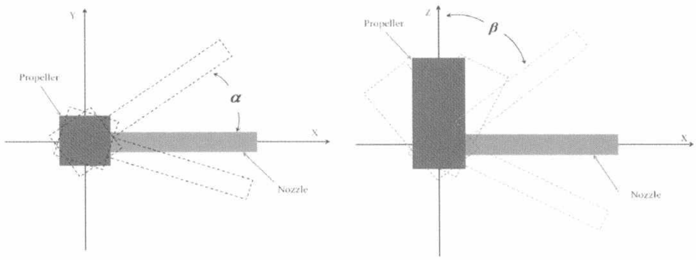
where R is the radius of the vehicle, $s(\cdot) \equiv \sin(\cdot)$ and $c(\cdot) \equiv \cos(\cdot)$.

So, a general transform matrix can be obtained:

$$^{p}\boldsymbol{P}_b = \boldsymbol{\Phi}_p^b \cdot {}^{p}\boldsymbol{P}_p + \boldsymbol{C} \tag{4}$$

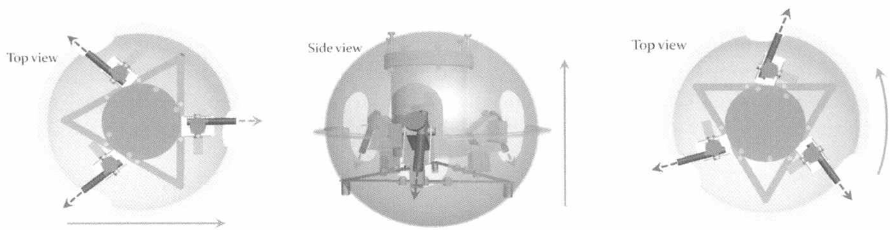
where $^{p}\boldsymbol{P}_b$ is the position vector of propeller-fixed coordinate expressed in vehicle-fixed coordinate, $\boldsymbol{\Phi}_p^b = (\boldsymbol{\Phi}_{p1}^b, \boldsymbol{\Phi}_{p2}^b, \boldsymbol{\Phi}_{p3}^b)^T$ is the transform matrix from propeller-fixed coordinate to vehicle-fixed coordinate, $^{p}\boldsymbol{P}_p$ is the position vector in propeller-fixed coordinate and the $\boldsymbol{C}$ is a constant vector.

Now, let us take a look at three motions, surge, heave and yaw. The definition of these three motions can be found in (Fossen, 1995). Before that, we define two angles which will be used for orientation of propellers. Fig.10 gives the definition of α and β. Fig.11 gives a demonstration of surge, heave and yaw.



(a) Rotation in X-Y Plane (b) Rotation in X-Z Plane

Fig. 10. Orientation of Propellers



(a) Surge (b) Heave (c) Yaw

Fig. 11. Propulsion Forces for Surge, Heave and Yaw

The first case is surge. In this case, two of the water-jet propellers will work together, and the other one could be used for brake. So, from Fig.11(a), two water-jet propellers in the left will be used for propulsion, and if we want to stop the vehicle from moving, the third propeller can act as a braking propeller. From Equation 4, the resultant force for surge can be expressed in vehicle-fixed coordinate as:

$$\begin{cases} {}^{p}F_{xb} = \boldsymbol{\Phi}_{p1}^{b^T} \sum_{i=1}^{3} ({}^{p}\mathbf{F}_{ip} + \mathbf{e}_1 C_i) \neq 0 \\ {}^{p}F_{yb} = 0 \\ {}^{p}F_{zb} = 0 \end{cases} \tag{5}$$