An underwater autonomous platform/vehicle

R S Bradbeer[1], H F Lai[2], M H Lee[2], T W Ying[2]

[1]Department of Electronic Engineering,

[2]Department of Manufacturing Engineering and Engineering Management

City University of Hong Kong, Tat Chee Avenue

Kowloon Tong, Kowloon, Hong Kong

eersbrad@cityu.edu.hk

Abstract: The objective of this project was to design and build an autonomous underwater platform that could reach a depth of 20m. It would be programmed with a trajectory, including horizontal and vertical motion, initially positioned using GPS. Inertial navigation would be used for part of the way, with recalibration of the position available via GPS if the unit surfaced. The platform would have a camera and the video signal would be compressed and recorded, along with navigational data, on the internal HDD. The platform would also be designed to carry instrumentation if required.

The ROV is designed to use four motors for horizontal positioning. Once the ROV arrives at the location to be reached, then it can navigate itself to a point underwater at a pre-established depth by using a depth sensor, and the on-board microprocessor can control the depth of the ROV. Finally by using position detection system such as GPS, the ROV can allocate to the given point directly and positioning at a fixed point for instrumentation or other jobs.

Keywords: Underwater platform, autonomous underwater vehicle, remote operated vehicle

Introduction

The Underwater Systems Group at City University of Hong Kong has a long association with underwater robotics [1-5]. This paper describes a remote and autonomous underwater vehicle designed and built by three final year undergraduate students as part of their final year project.

The prototype of the ROV is designed to use four motors for horizontal position instead of two. This is because the performance using two motors to control the movement and stability is not as good as four motors.

Normally, for two motors, when the underwater vehicle wants to position itself into a new coordinate, it has to rotate itself into the angle pointing to that coordinate and then go straight to that position.

The prototype of the ROV has four motors, but in order to move the ROV to a fixed position there are only three variable (Fx - the force in the x coordinate direction, Fy - the force in the y-coordinate direction and T, the torque on the platform to trun it in a direction). However, there are four equations generated for the motion of each motor, only 3 unknowns. Thus we need to fix one motor with zero or a constant.

After the equations are solved by using matrix, the magnitude for each motor can calculated by the on-board microprocessor.

Once the ROV arrives the target location, it can navigate itself to a point underwater at a pre-established depth by using a depth sensor, and the on-board microprocessor can control the depth of the ROV. The on-board processor consists of a laptop pc with its keyboard removed. Control of the laptop is through a wireless keyboard attached to one of the usb ports.

Finally by using position detection system such as GPS, the ROV can allocate to the given point directly and position itself at a fixed point for instrumentation or other jobs.

Co-ordinate system transformation and horizontal position of the rov

When we calculate the force on the ROV, we need to study the coordinate system transformation. We take the earth's coordinate as the absolute coordinate and the coordinate of the ROV as relative coordinates

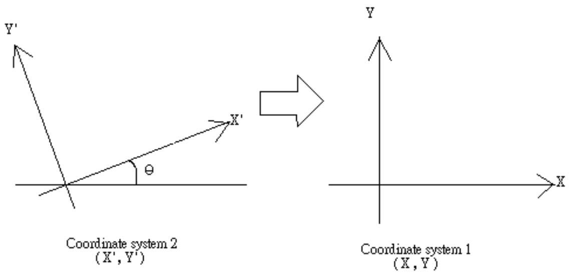

Figure 1

In Figure 1 there are two coordinate systems, coordinate system 2 is relative coordinate of the ROV and coordinate system 1 is the absolute coordinate of the earth. Let us transforme coordinate system 2 into coordinate system 1 which makes an angle θ, in matrix form;

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} X' \\ Y' \end{pmatrix}$$

Then relative coordinates can transform to absolute coordinates. For the initial design, the motors were set at an angle of 70°.

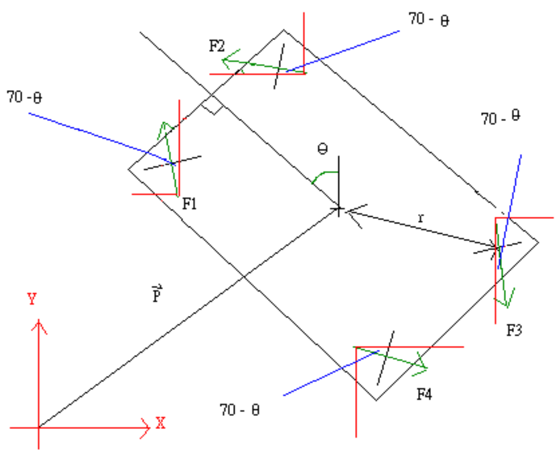

Figure 2 Vector definitions of the ROV

X-Y absolute coordinate (the earth)
X'-Y' relative coordinate (the ROV)
P position vector of the ROV
R direction vector of the ROV
θ angle between R and P
r distance between the centre of ROV to each propeller
F1 force (vector) of motor1
F2 force (vector) of motor2
F3 force (vector) of motor3
F4 force (vector) of motor4

and if

F1 =

F2 = $\alpha_2 \bar{\alpha}_2$

F3 = $\alpha_3 \bar{\alpha}_3$

F4 = $\alpha_4 \bar{\alpha}_4$

a matrix can be derived, and it can be shown that there are only 3 variables (Fx, Fy and T), but with 4 unknowns (α1, α2, α3 and α4), so we take one unknown with constant in order to solve the matrix.

By putting α4= 0, then we can solve for α1, α2, and α3,

$$M_1 = \begin{pmatrix} \dfrac{-\sin\theta}{2\sin 70^\circ} & \dfrac{\cos\theta}{2\sin 70^\circ} & \dfrac{-1}{2r} \\ \dfrac{-\sin(70^\circ+\theta)}{\sin 140^\circ} & \dfrac{\cos(70^\circ+\theta)}{\sin 140^\circ} & 0 \\ \dfrac{-\cos\theta}{2\cos 70^\circ} & \dfrac{-\sin\theta}{2\cos 70^\circ} & \dfrac{-1}{2r} \end{pmatrix} \begin{pmatrix} Fx \\ Fy \\ T \end{pmatrix}$$

and

$$M = \begin{pmatrix} \alpha 1 \\ \alpha 2 \\ \alpha 3 \end{pmatrix}$$

By solving the matrix, the value of $\alpha 1, \alpha 2, \alpha 3$ can be calculated.

Mechanical design

The case is composed of 4 main parts: the shell, cover and the front and rear triangular shape which are made of plastic named Polymethyl Methacrylate. This material is cheap, easy to machine, hard but is too brittle. As a result, the thickness of plastic is 12mm to make the whole case strong enough to cope with the external pressure of up to 10m of water (about 3 bar).

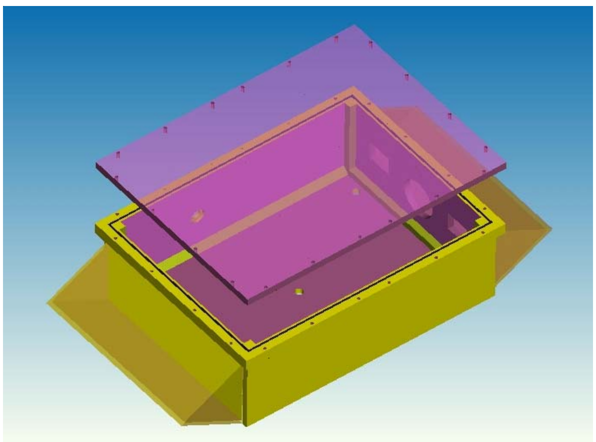

Figure 3 Exploded view of the case

As shown in Figure 3, the front part has three holes. The circular one is for the camera, while the rectangular ones are for cables as well as allowing inspection of the interior.

In order to make the case stronger, a number of ribs are put at the joint. Another purpose of these ribs is to prevent leakage. There is another hole in the side of the case which allows the depth sensor to be fitted into the case. At the bottom of case, there are a number of other holes. They are used to fix the thrusters, the piston adaptor, and the ROV frame.

Another feature of the shell is the groove for the o-ring to lie on. There are 20 holes to attach the cover. The motion of our ROV is mainly moving forward and backward. Two triangles are attached to the front and rear of the case to make the ROV become streamlined. This design not only reduces the load of the thrusters, but also makes the ROV movement more stable because the ROV can easily overcome the ocean wave during movement. There are two other advantages arising from these triangles: reduce the density of the ROV, and allowing the placement of camera in better position.

There is an aluminium frame to support to weight of case, pistons and thrusters, as well as to provide protection to the motors when in transit or when used in rough underwater terrain, like a coral reef. At the four corners, there are cylinder shape spongy materials which are used to absorb any impact. The finished case and frame is shown in Figure 4.

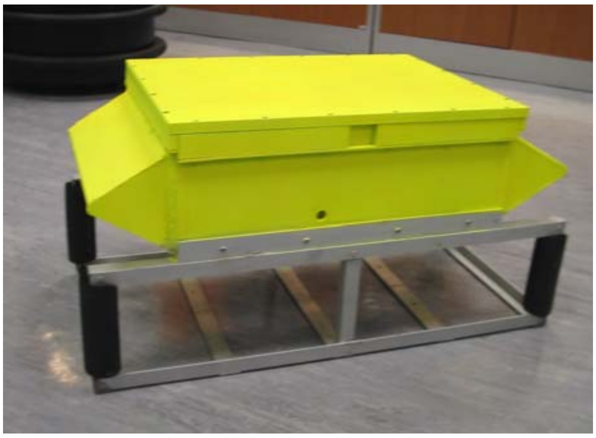

Figure 4 The finished case and frame

The thruster design

As there were no readily available thrusters at a reasonable cost, it was decided to make them. It was decided, after experimentation and simulation, that four 12 V motors of 30 W, with a no-load rated

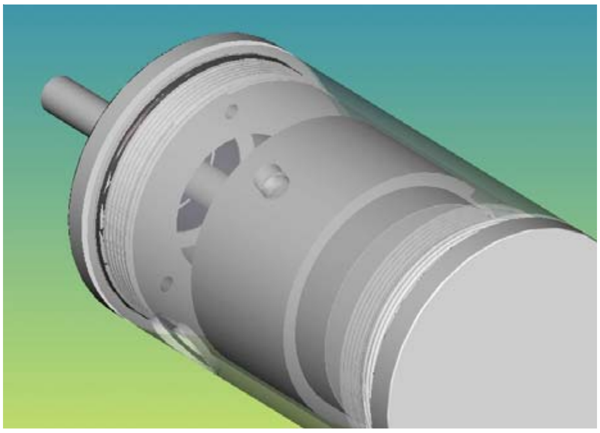

Figure 5 Assembled view of the thruster

Figure 6 Some parts of the thrsuter

Figure 7 The assembled thrusters

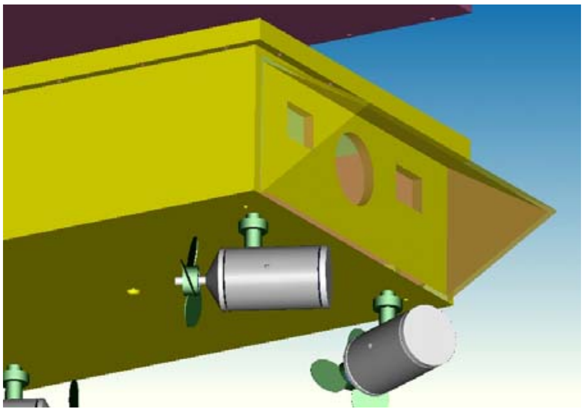

Figure 8 Showing the adaptors fixing thruster to chassis

speed of 3000 rpm would be used. These would also have a feedback mechanism to allow closed loop control.

The thrusters are made by aluminium because of its light weight; they are basically cylinders with covers at both ends. They are fixed to the ROV chassis with an adapter that can rotate, so that the thrusters can be moved into the most efficient position. Figures 5 - 8 show various views of the thrusters. The shafts were sealed o-rings for the cylinder end-caps, and lip-seals of polypropelene rubber.

The feedback from the motor for the control system was from a small dc motor that was attached by gears inside the thruster housing - see Figure 9. Each thruster was calibrated against a tachometer to overcome any non-linearity in the voltage generated. A zero and span circuit was used to linearise the characteristics, as well as to match the output to the ADC providing the digital feedback to the controller.

Figure 9 Feedback motor in thruster body

The buoyancy system

A piston is used to control the vertical motion of the underwater vehicle by sucking water into the vehicle, thus increasing its weight, causing it to sink. When the motor rotates in reverse direction, thus pushing water out of the vehicle, then the weight of the vehicle decreases, and the underwater vehicle will rise. When the pistons are mounted together with the case, then the whole vehicle will become a close system. That means no air can escape or enter the vehicle. Thus when the piston is sucking water, it actually compresses the air inside the vehicle. On the other hand when the piston is pressing the water out off the vehicle, it has to work against the water pressure from outside. This meant that it was necessary to calculate the pressure and force required for the motor. It was decided to use two pistons, balanced and mounted at the centre point of the casing, on the frame.

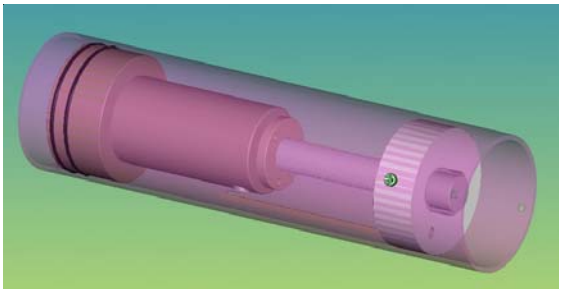

Figure 10 Structure of the piston

The motor used was a 12V, 5000rpm dc motor, geared down to 60rpm. It had a torque of 600N/m. This was able to provide the 270kg force required to expel water at a depth of 10m. Figure 10 shows the structure of the piston, and Figures 11 and 12 show the two-piston structure and the detail of the piston design.

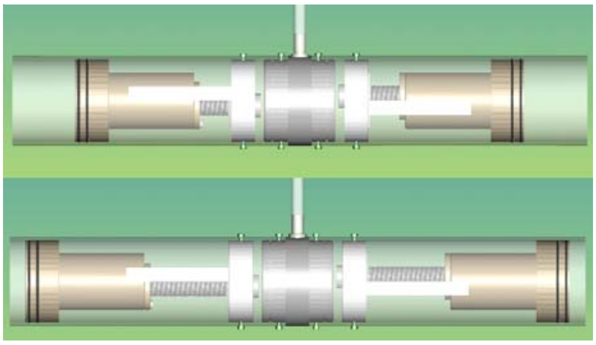

Figure 11 The two-piston structure

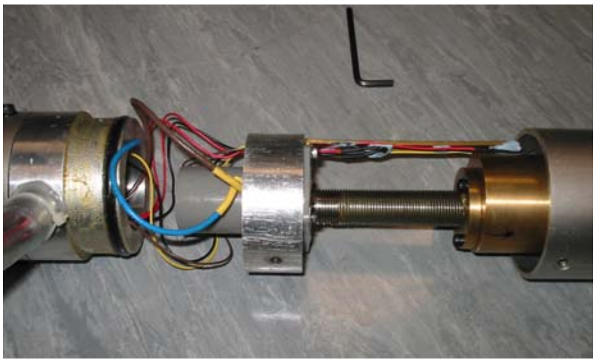

Figure 12 The piston detail

The camera system

The ROV used a simple web-cam to record video in mpeg1 format on the HDD of the main computer. However, it was also possible to view the picture from the camera whilst the ROV was on the surface, or for extracting the video from the HDD when the ROV was on land.

Consequently, a simple vga-tv signal converter was used with an rf video link at 2.4GHz. This allowed a normal tv to be used. The webcam used also had the ability to digital zoom, or to pan and tilt.

Digital compass and pressure transducer

As well as recording video on the HDD, data from the on-board instrumentation was also recorded. The ROV had an on-board digital compass, that could be used either for recording data, or for controlling the direction of the ROV whilst underwater.

The system used a PNI V2Xe integrated 2-axis compass and magnetic field sensing module [6] featuring an on-board microprocessor for control and interfacing. The microprocessor controls an ASIC and provides access to the V2Xe's heading information as well as magnetic field measurement data for the interface to the main computer.

The depth of the ROV was measured using a 0-1 bar pressure transducer. This had an output of 0 - 100mV, and was interfaced to the main computer via an amplifier with a gain of 20 and a 12 bit ADC.

Main computer

The main computer consisted of a Pentium 2 366Mhz IBM laptop computer with its lcd display disconnected. All peripherals were connected via the on-board interfaces, including serial port, parallel port, usb ports and video out. The general system diagram is shown in Figure13.

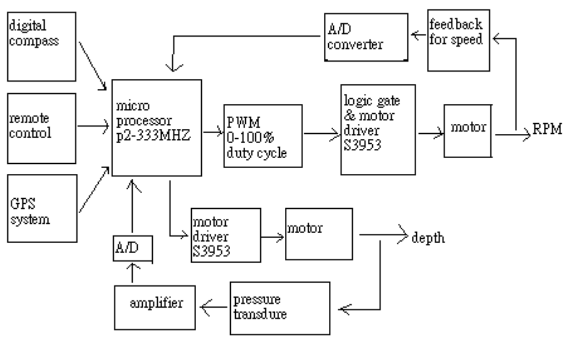

Figure 13 General system diagram

The pc had 128Mbytes RAM, 2Gbytes harddisk storage size, one USB port, parallel and serial port and with VGA output.

There were a number of reasons to use a laptop pc as a controller:

*As the ROV contains one USB web cam, any controller must contain at least one USB port. A Stamp size PC with USB port is suitable but the cost is too high.

* The pc contains a large storage size so that the OS system and the video recording can be stored onto the HDD without problems. As the laptop is designed for portable users, the HDD is well damped and can resist shock.

* The processor speed is higher than the Stamp size PC.

However, the weight of a laptop is heavy, therefore some parts were disassembled - the PCMCIA socket, LCD monitor, battery and CD-ROM drive. The photo of laptop after disassembly is shown in Figure 14. The keyboard was left on, as it provided an easy method of communicating with the ROV when it was on-shore with the top of the case removed. It was also possible to use the pre-installed Windows OS, which was already configured for the i/o.

Figure 14 Disassembled laptop

Since the main controller is a laptop, its Parallel Port was used to interface with external circuitry. As the parallel port is digital interface, it is easier to generate the PWM to run motors, read the digital signals and communicates with the logic ICs. The standard PC's parallel port has 8 outputs, 5 inputs and 4 bidirectional lines. It can transfer eight bits at once to a peripheral. The SPP doesn't have a byte-wide input port, but it can use a Nibble mode that transfers each byte 4 bits at a time.

Motor control

The main power on the ROV was supplied by two 12V lead-acid accumulators. One provided the supply for the pc and instrumentation, the other for the motors. The motors used an A3953S full-bridge pwm motor driver [7].

The parallel port only has 8 output pins. Each motor drive IC needs 2 inputs (enable and phase signals). So, in order to control 4 thrusters, 8 outputs

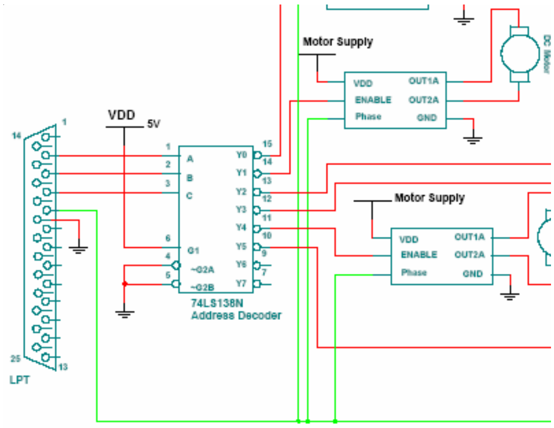

Figure 15 Motor control circuit showing address decoder on pc parallel port

pins are needed. We also need to use some of the bi-directional lines to control other devices. The solution is to use an address decoder, as shown in figure 15, then only 3 output pins from the parallel port are needed to give 8 outputs.

In this ROV, there are 6 motors. Thus, this circuit can control up to six motors and the remained two output pin can be for other uses. The phase signal (direction of motor) connects to all six drive ICs, but the interconnection will not cause any problem because when one motor is ON, the others are OFF no matter what phase signal is. Thus, we effectively have multi-tasking. If the switching time and controlling time of each motor are short, it seems that all motors are running at the same time.

The design of the ROV would not allow horizontal and vertical motion simultaneously, we tested the two type of motion separately. This showed up one problem with this approach. If the four thrusters are run at the same time, they can't run at the same speed. Two of them are about 200 - 400 rpm under 100% duty cycle. However, when we didn't use the multi-tasking method, these two motor can run faster about 1000-1300 rpm under full duty cycle. When we reduce the number of motor to be controlled to 3, the performance was better.

For the buoyancy, the two motors can run at the same speed. So, the performance of vertical motion is better than that of the horizontal.

Initially, this problem was rectified by using some optical encoders on the thruster shaft. The rotation speed information was fedback to the controller using small encoder discs, as shown in Figure 16.

However, this did not prove entirely satisfactory, and it was decided to use a small dc motor to provide the feedback, as shown in Figure 9. This solved most of the problems.

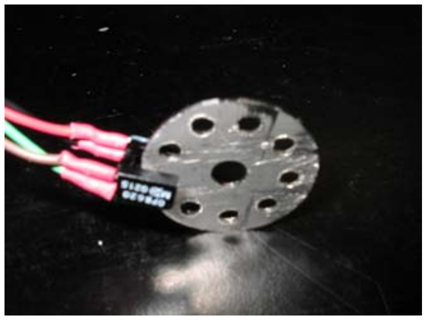

Figure 16 Optical encoder

Performance

The ROV performed well in its laboratory tests. It was initially controlled using a radio linked keyboard
to a small wireless keyboard receiver in one of the USB ports. This allowed the ROV to be programmed with its path and depth information. The digital compass was only setup for giving heading information in these tests. The buoyancy system worked well, but had so much inertia that it proved difficult to control the depth as precisely as planned.

Figure 17 ROV in test pool

Future options include replacing the dc motor driven buoyancy system with a hydraulically powered one. This should make the response much quicker. Secondly, the thrusters could be more efficient. And finally a more robust case design, that would be reliable at greater depths, would be considered.

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References

[1] R Bradbeer, S Harrold, B L Luk, Li B, L F Yeung and Ho H W, "A mobile robot for inspection of liquid filled pipes", Workshop on Service Automation and Robotics, City University of Hong Kong, June 2000

[2] R. Bradbeer, S. O. Harrold and L. F. Yeung, "An underwater robot for pipe inspection", Mechatronics and Machine Vision in Practice, Queensland, Australia, Sept. 1997

[3] F Nickols, R. Bradbeer and S O Harrold "An ultrasonically controlled autonomous model submarine operating in a pipe environment", Mechatronics and Machine Vision in Practice, Queensland, Australia, Sept. 1997

[4] Ho H W, Bing L and R Bradbeer, " The design of a hydraulically powered leg for an underwater six-legged robot", in Mechatronics and Machine Vision, (J Billingsley (Ed)), Research Studies Press, UK, pp 263-274, 2000

[5] R Bradbeer, "The Pearl Rover underwater inspection robot". in Mechatronics and Machine Vision, (J Billingsley (Ed)), Research Studies Press, UK, pp 255-262, 2000

[6] PNI Corp, http://www.pnicorp.com/productDetail?nodeId=c39b

[7] Allegro Microsystems Inc. http://www.allegromicro.com/datafile/3953.pdf