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# Development of a dual-shaft propeller thruster equipped with rotational speed sensor for UVMS control

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**Abstract:** Majority of underwater robots utilize single propeller thrusters for navigation. A disadvantage on using a single propeller thruster is the thrust force generated from a single propeller for reverse and forward thrust is asymmetric due to the disturbed flow caused by the thruster's body which may reduce thruster efficiency. Measurement procedures to precisely calculate propeller's rotation speed were also not available. To address these problems, this paper proposes a dual-shaft magnetic coupling driven propeller thruster for underwater vehicle-manipulator system (UVMS) equipped with sensors for measuring propeller's rotational speed. Numerical studies and experimental results on the position and orientation control of the proposed thruster are presented. Detail comparison of the rotational speed, thrust force and duty-ratio between numerical calculation and actual experimental measurement results shows the effectiveness of the proposed thruster. The ability to determine propeller rotation directions is also a major advantage.

**Keywords:** dual-shaft, thruster, rotational speed, UVMS, control

## 1 INTRODUCTION

The main purpose of this research is to design a new underwater thruster for an underwater vehicle-manipulator system (UVMS) equipped with a 2-link manipulator which the authors have been actively carried out [1-3].

To date, a large number of underwater robots utilize single propeller thrusters for navigation [3-6]. A disadvantage on using a single propeller thruster is the thrust force generated from a single propeller for reverse and forward thrust is asymmetric due to the disturbed flow caused by the thruster's body which may reduce thruster efficiency. A magnetic coupling driven propeller thruster transmits torque through an air gap between motor driven shaft and load shaft (propeller). However, due to magnetic coupling mechanism, it is difficult to measure precisely the actual rotational speed of the propeller and the thrust generated from it. Although there are researchers demonstrating the relation between propeller's torque rotational speed and the generated thrust, they utilized unknown parameters and only focusing on motor driven propeller thruster without magnetic coupling. Measurement procedures to specifically calculate propeller's rotation speed were also not available.

To address these problems, this paper proposes a dual-shaft magnetic coupling driven propeller thruster for UVMS equipped with sensors for measuring rotational speed of the propellers. The developed thruster is consists of two magnetic coupling driven propellers which rotate in directions opposite one another. Magnetic coupling mechanism has been selected, due to the several advantages such as cushioned start, low power usage and low maintenance cost. The paper also proposes a method on calculating the propeller thruster's thrust force through measuring rotational speed and thrust forces generated from the propellers and compared it with commercially available thruster for performance comparison.

## 2 DESIGN METHODOLOGY

### 2.1 Thruster design

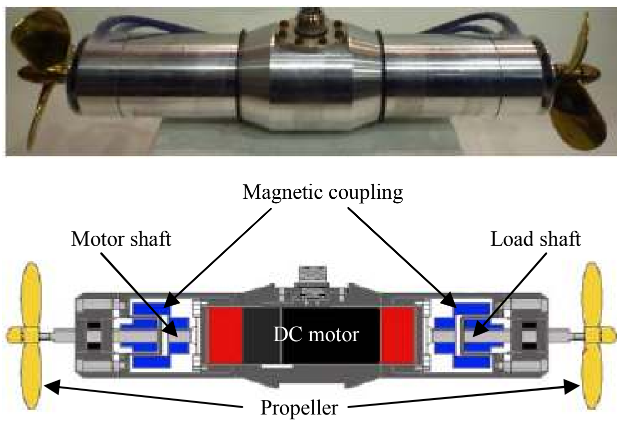



**Fig. 1.** Dual-shaft magnetic coupling propeller thruster

In this section, the developed dual-shaft propeller thruster driven by co-axial magnetic coupling is described. Fig.1 shows the developed thruster. Basically, one of the magnets is driven by a motor through a motor shaft. This mechanism is designed inside a waterproof container. The other magnets is connected to the propeller via a load shaft. Two Raboesch 3-blade brass propellers are being used. A dual-shaft Faulhaber 3863A024C DC motor with planetary gearheads is being used to drive two sets of MTL-03 co-axial magnetic coupling from Magnetic Technologies. The motor is controlled by a PIC30F3010 microcontroller. Table 1 shows the physical parameters of the developed thruster.

**Table 1.** Physical parameters of thruster

| | |
|---|---|
| Length | 383 [mm] |
| Outer diameter | 57 [mm] |
| Weight | 3130 [g] |
| Propeller pitch | 102.5 [mm] |
| Propeller diameter | 100 [mm] |
| Propeller weight | 84 [g] |


(a) (b)

**Fig. 2.** Reflective photosensors and metal disk position

### 2.2 Reflective photosensor

The rotation speed of the propellers can be measured by using two units of RPR-220 (ROHM Co. Ltd.) reflective photosensors embedded in both of the motor shaft housings facing towards the propeller as shown in Fig.2 (a). The reflective photosensors consists of an infrared emitted diode and a phototransistor which can detect the reflected infrared light. The infrared light is reflected by a metal disc which is attached on the propeller's shaft, located between the propeller shaft housing and propeller as shown in Fig.2 (b). The metal disc will rotate along with the propeller. It is carved with 8 holes and layered with thin black colored rubber attached on the back of the discs which is to prevent infrared reflection. The metal reflective surface and black colored rubber surface makes a perfect reflecting and non-reflecting surfaces.

### 2.3 Rotational speed measurement

As described in the previous section, propeller's rotational speed can be measured using two units of reflective photosensors embedded side by side. The sensors are embedded in such a way that provides two voltage outputs with the phase differences of 90°. When the propeller and metal disc rotated, the rotational speed can be calculated by the embedded sensors. Moreover, the voltage outputs phase differences of 90° provide the ability to determine the directions of rotation for both propellers. The metal discs have 8 holes, where 1 rotation of the propeller produces 32 pulse (11.25°/pulse). The relationship between number of pulse and rotational speed is expressed with

$$R = \frac{60 \times P}{32 \times T} \tag{1}$$

where $R$ is propeller's rotational speed (unit: rpm), $T$ is sampling period (unit: s), $P$ is number of pulse between a sampling period.

To control thruster's force, the desired rotational speed which corresponded to the desired thrust force need to be calculated. The desired rotational speed can be calculated by the following equation:

$$R_{d_i} = 0.1576\, f_{d_i}^{\ 3} - 6.075\, f_{d_i}^{\ 2} + 112.2 f_{d_i} + 136.7 \tag{2}$$

Here, $d_i$ is desired thruster number $i$ ($i$=1, 2), $R_{d_i}$ is the desired rotational speed (unit: rpm), $f_{d_i}$ is the desired thrust force (unit: N). While the desired input signal which correspond to the desired rotational speed can be calculated by the following equation:

$$\begin{aligned} u_{d_i} &= 0.913 \times 10^{-7} R_{d_i}^{\ 3} - 5.292 \times 10^{-5} R_{d_i} \\ &\times 10^{-5} R_{d_i}^{\ 2} + 4.298 \times 10^{-2} R_d - 2.786 \end{aligned} \tag{3}$$

Where $u_{d_i}$ is the desired input signal (duty ratio, unit: %).

Based on these desired thrust, rotational speed and input signal calculated in equation (2) and (3), and also rotational speed measured through reflective photosensors, $R_i$ in equation (1), the actual input signal $u_i$ for the thruster can be calculated as below:

$$u_i = u_{d_i} + k_P (R_{d_i} - R_i) + k_I \int (R_{d_i} - R_i) dt \tag{4}$$

Here, $k_P$ is proportional gain and $k_I$ is integral gain.

## 3 EXPERIMENTAL SETUP

### 3.1 Thruster control system experiment

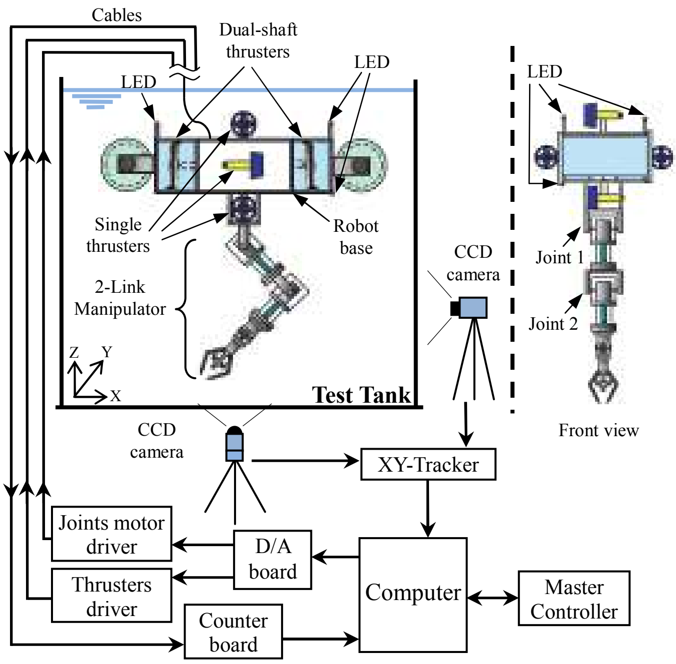
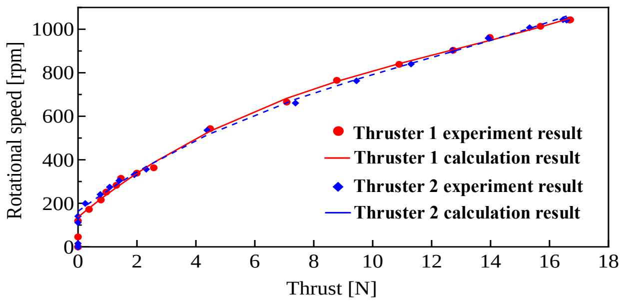



**Fig. 3.** Experimental setup for the developed thruster

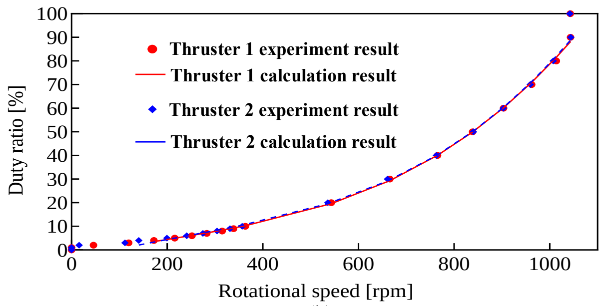
Fig.3 shows an illustration of the experimental setup for the developed thruster on an UVMS to measure the robot position and orientation. Two of the proposed thrusters were attached on the robot as shown in Fig.3, and then compared with two commercially available single propeller thrusters. Three LEDs are attached to the robot base, and their motion is monitored by CCD cameras. Video signals from the LEDs are converted into position data by X-Y tracker and transmitted to PC for calculation of the positions and orientation of robot base. Robot control is achieved using resolved acceleration control (RAC) method with sampling period of T=1/60sec [1-3]. For experiments using the developed thrusters, the gain for rotational speed control are set as $k_P = 0.031$, $k_I = 0.0017$.

## 4 RESULTS

Experiments have been carried out on two newly developed propeller thrusters. Firstly, based on the calculations of desired thrust, rotational speed and input signal described in section 2.3, performances comparison with actual measurements using reflective photosensors on two proposed thrusters has been implemented. Fig.4(a) and Fig.4(b) shows the relation between rotational speed, duty ratio and generated thrust force. Fig.4(a) shows that measurement results of the increased in duty ratio on propeller's rotational speed from both thrusters have similar performances with calculated results. Fig.4(b) shows that an increase of rotational speed resulting in increase of thrust force. The measurement results also gave similar performance with calculation results which demonstrated the usefulness of the proposed thrusters equipped with reflective photosensors for rotational speed measurements.




(a)




(b)

**Fig. 4.** (a) Relation between thrust and rotational speed, (b) relation between speed and duty ratio

Next, Fig.5 and Fig.6 shows experiment results for position and orientation of UVMS. Based on the experimental setup in Fig.3, the robot base was controlled to move 0.15m downward. The results of position and orientation (x, y, z, roll, pitch and yaw axes) from the robot base using the traditional single propeller thrusters and the proposed dual-shaft propeller thrusters are shown in Fig.5 and Fig.6 respectively. Fig.5 shows that the commercially available single propeller thrusters produced large vibration on x axis during the first 20sec from the start of movement. Large vibrations also recorded in y and z axes, during the first 20sec and 40sec respectively. Orientation of the base also demonstrated large vibration for the first 40sec. However, Fig.6 shows that by using the proposed thrusters, UVMS demonstrated no large vibration occurrence on position and orientation axes. The above results proved that the proposed thrusters design demonstrated good performance compared to the commercially available thrusters.

## 5 CONCLUSION

A dual-shaft magnetic coupling driven propeller thruster for underwater vehicle-manipulator system (UVMS) equipped with sensors for measuring propeller's rotational speed have been proposed. Numerical studies and experimental results on the position and orientation control of the dual shaft propeller thruster shows the effectiveness of the developed thruster. The ability to determine propeller rotation directions is also a major advantage.

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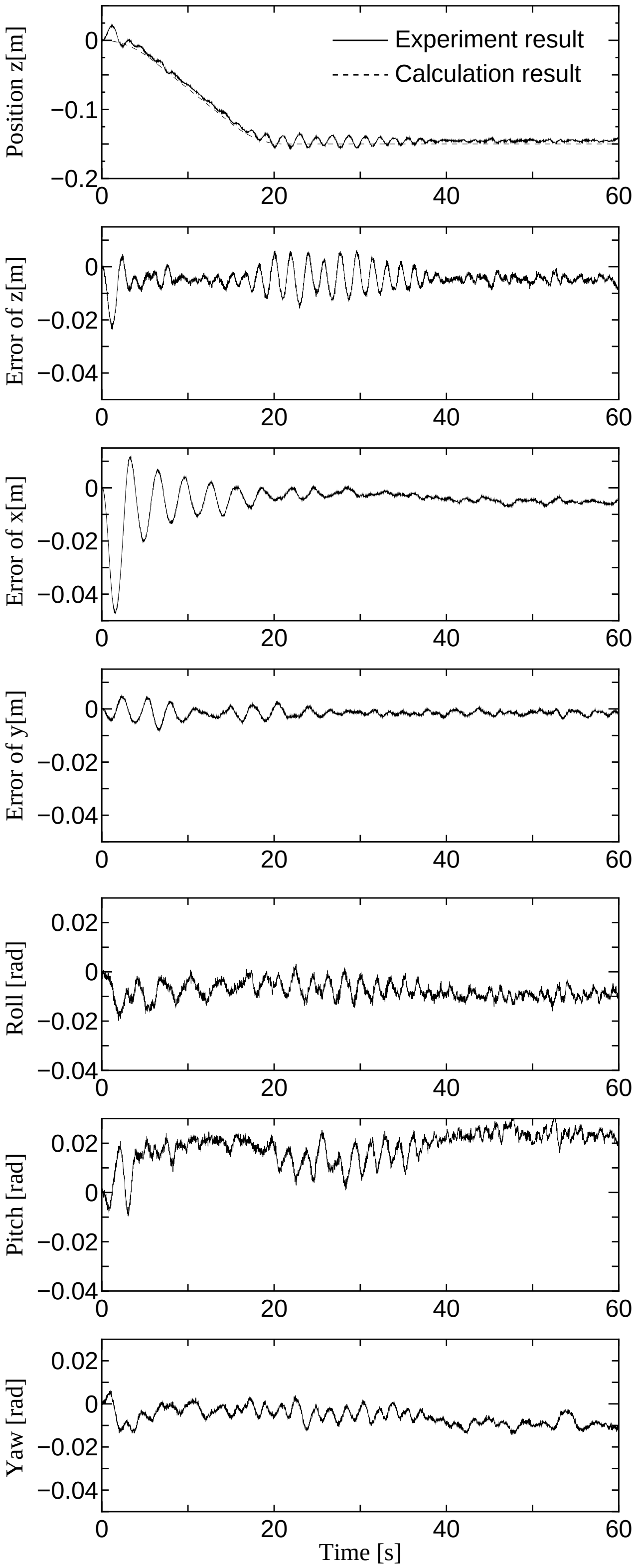


**Fig. 5.** Experimental results using commercial thrusters

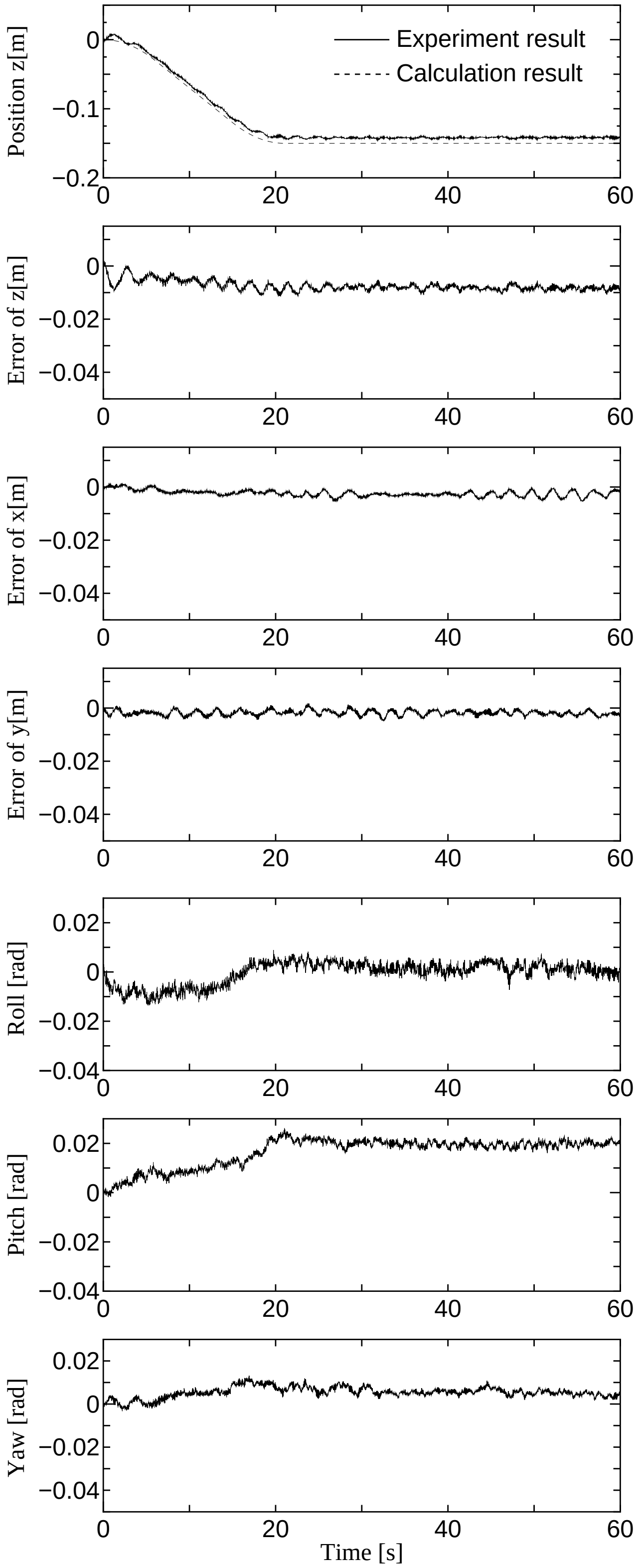


**Fig. 6.** Experimental results using proposed thrusters