IMPROVING ROV CONTROL PERFORMANCE WITH THRUST IDENTIFICATION AND CONTROL

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Abstract: The problem of improving control performance of a Remotely Operated Vehicle with thruster modelling and identification and with Thrust Allocation Logic (TAL) is discussed. This is done in the context of the developments of "IES - Inspection of Underwater Structures" project. The IES ROV is mechanically asymmetric as a result of design trade-offs intended at reducing weight and facilitating operational deployments. Experimental data from tests with this ROV shows that control design under symmetry assumptions leads to poor control performance. A significant modelling effort was required to improve control design and performance. The modelling effort is concentrated on the force system acting upon the ROV body and also on thruster characterization. The nonlinear controllers were tuned for the enhanced model parameters and a new control stage – TAL – was designed and implemented. The new integrated control design was validated experimentally.

Keywords: Remotely Operated Vehicles, Underwater Inspection, Thrust Allocation Logic, Thruster Identification.

1. INTRODUCTION

The IES – Inspection of Underwater Structures project concerns the design and implementation of an advanced low cost system for the inspection of underwater structures based on a Remotely Operated Vehicle (ROV). Examples of missions are: evaluation of the state of corrosion of submerged steel plates and of the conservation state of underwater structures, inspection of ship hulls, and also detection and visualization of archeologic artifacts. The project started in 1999, lasted for 3 years, and was funded by PROGRAMA PRAXIS XXI - MEDIDA 3.1B, Portugal. IES is a collaborative project involving the Administração dos Portos do Douro e Leixões (APDL) and the Underwater Systems and Technology Laboratory (USTL) from Porto University. The laboratory was founded in 1997 to promote research, development, deployment, and operation of advanced systems and technologies in oceanographic and environment field studies. Today, USTL aggregates close to 20 researchers including Faculty, Ph.D. and M.Sc. students, and engineers. The USTL started developing and operating the *Isurus* Autonomous Underwater Vehicle in 1997. Since then, the USTL designed and developed: 1) Remotely Operated Vehicle (ROV) for the inspection of underwater structures; 2) low cost AUV for coastal oceanography (Cruz *et al.*, 1999); 3) low cost sensor modules for remote environmental data collection; 4) acoustic navigation technology for multiple AUVs (Matos *et al.*, 1999); and 5) feasible concepts for the networked operation of multiple vehicles and systems (Girard *et al.*, 2001). Over the last two years the USTL devoted an intense effort to the development of feasible concepts for the networked operation of multiple vehicles and systems, and the first deployments are scheduled for late 2004.

The ROV hull is a customized version of a Phantom 500 model from Deep Ocean. The USTL developed all the major ROV systems (refer to section 2). The ROV is physically asymmetric and its principal motions on x, y, z and yaw became highly coupled in open-loop motions. To overcome this problem, we tried to compensate the asymmetries by distributing some plates in appropriate places. The idea was to restore its symmetry. Unfortunately, this was not enough. This is why we had to design the Thrust Allocation Logic (TAL) module. To accomplish this, it was necessary to obtain a good model of each thruster. This model predicts the force generated by each thruster as a function of the propeller revolution. To define the correct allocation, we studied all forces acting on the vehicle while it is moving with constant speed. This paper is organized as follows. In section 2, we describe the main sub-systems of the IES system. Section 3 presents an example of a typical mission. Section 4 presents the ROV thruster model and gives an idea how the experiments were conducted at USTL to obtain data for parameter identification. Section 5 describes the allocation strategy. Finally, section 6 ends with some concluding remarks, and future work.

2. SYSTEMS

Except for the ROV frame, hull and thrusters, all of the other components and systems were designed and implemented at USTL. The ROV frame, hull and thrusters are a customized version of the Deep Ocean 500 S model from Deep Ocean Engineering. The main mechanical difference with respect to the standard model is an additional cylinder that houses electronics and sensors.

The IES system integrates the following innovative technologies and systems developed at the Underwater Systems and Technology Laboratory (LSTS) from Porto University:

- Acoustic navigation system (Cruz *et al.*, 2001), (Matos *et al.*, 1999).
- Advanced control systems.
- Power and motor control.

In the basic configuration the IES system comprises the following systems:

Fig. 1. On the left the starboard cylinder with an electronic compass and the dimmer and motor controllers. On the right the port cylinder with the on-board power supply system and also it's monitor.

Fig. 2. On the left the inertial system and on the right the PC104 CPU stack

Computer system - Consists of a PC-104 stack running the real-time QNX operating system on the vehicle, and a Windows based PC connected through an Ethernet cable. The PC-104 stack is housed in the main cylinder of the ROV, and controls the ROV hardware through a CAN bus (fig 2 on the right). Some systems also have an RS-232 interface, and therefore a PC-104 RS-232 board was added on the stack. Additional sensors are interfaced through an A/D card on the PC-104 bus. The Windows based PC runs the operator console. The PC also runs a Web server providing Web-based access to obtain data from operations, while ROV control is restricted to the operator console. The PC-104 computer system runs the command, control and navigation software. Basically, this computer accepts high-level commands from the console, and informs the console about the system state.

Power system - A portable generator provides electrical power to the system. The umbilical cable feeds the ROV with two main power lines 120V DC / 1,2KW and 48V / 100W. The first power line feeds DC motors and lights. The other line feeds the on-board electronics. Inside the ROV, there is a power conversion unit (fig 1 on the right) to generates all of the required voltage levels. Those levels are achieved with dc-dc converters. This arrangement of the power system minimizes the number of wires in the umbilical cable and consequently its weight. This design option is aimed to minimize the effects of the tether on the ROV dynamics, one of the traditional difficulties associated with ROV operations.

Motor control system - This system comprises two CAN nodes housed in the two upper vehicle

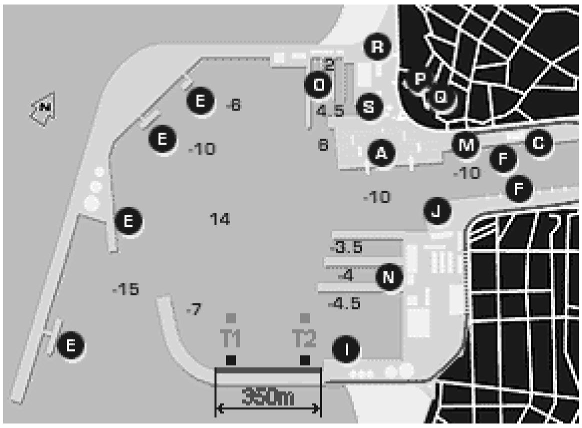

Fig. 3. APDL harbour map

cylinders. The controllers generate the reference PWM signals to the four thruster power drives. The DC motors are powered by these drives.

Navigation system - The suite of navigation sensors includes the on-board sensors and external ones (Cruz *et al.*, 2001), (Matos *et al.*, 1999). The available sensors are: magnetic compass, inclinometers, inertial navigation unit, depth cell, altimeter, Doppler Velocity Log (DVL) and LBL acoustic positioning system.

The acoustic system uses two acoustic beacons. In normal operation, the ROV system sends an acoustic signal to each beacon and waits for their response. The time that takes from the transmission to the reception gives the distance between the ROV and each of the acoustic beacons. The DVL sensor gives the velocity of the vehicle relative to water or relative to ground. The inertial navigation unit is also housed in the ROV (fig 2 on the left). The vehicle's depth is measured by the pressure sensor. The compass (fig 1 on the left) gives measurements of the orientation of the vehicle. It also measures the roll and pitch angles. We use an altimeter to measure the distance of the ROV from vertical walls.

We developed a sensor fusion algorithm to estimate all of the state variables, which are three positions, three orientations, and six velocities.

Vision system - In the basic configuration, the vision system consists of a camera mounted in a pan-and-tilt unit and a spot light. The video image is converted to the digital format in the on-board frame-grabber, and sent to the operator console through the Ethernet connection.

The basic inspection configuration can be enhanced with a set of plug-and-play inspection and intervention tools. This set comprises another vision system and an array of magnetic sensors. Other tools that are being considered for development include a tactile sensor array, and a scraping device.

3. MISSION EXAMPLE: APDL 18-10-2002

The Port of Leixões comprises the largest seaport infrastructure in the north of Portugal and is one of the most important seaports in the country. With 5 km of quays, 55ha of embankments and 120ha of wet area, Leixões has excellent road, rail and maritime accesses and is equipped with advanced information systems for vessels traffic control and management. Representing 25% of the Portuguese foreign trade (about 10 Million Euros of goods) and handling 14 million tons of commodities a year, the Port of Leixões is one of the most competitive and versatile multi-purpose ports in the country. 3,100 vessels a year come through Leixões, carrying all sorts of goods: textiles, granites, wines, timber, vehicles, cereals, containers, scrap metal, iron and steel, alcohol, schnapps, sugar, oil, molasses, petroleum products, and even passengers from Cruise Liners (*APDL*, n.d.).

In what concerns the visual inspection of underwater infrastructures for maintenance, the challenges involve the determination of:

- The state of corrosion of submerged steel pillars.
- The state of hull corrosion of all kinds of vessels.
- The state of the quay stone walls. The walls are subject to high pressures due to the motions of some types of thrusters.

In what follows we describe a typical inspection mission. The objective of this mission is to check the state of the quay wall marked with a solid red line close to the I letter in figure 3. The quay is 350 meters long and the average depth is 7 meters which leads to an area of inspection of almost $2500m^2$. This wall is made of stone blocks. The visual inspection consists in determining whether the stone blocks are correctly positioned.

3.1 Mission setup

There are two ways to operate the ROV at the APDL facilities: from a small boat or from the quay. We choose to operate it from the quay. For this mission there are two possible ways to determine localization for the vehicle navigation. One of them is to install the transponders in a way that we get absolute positioning measures on both x and y DOFs (Degree Of Freedom) horizontal plane. The other is to get measures on only one degree of freedom (x or y). The difference between both approaches is on the way that the transponders are installed.

Traditionally, we moor the two transponders (T1, T2) away from the wall in order to measure the

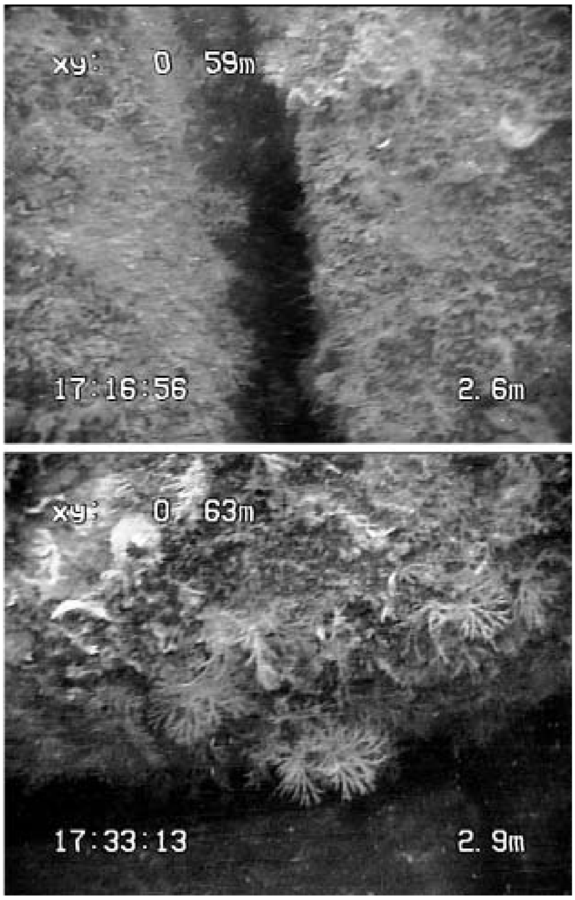

Fig. 4. Images captured by the vehicle. a) The upper image displays fissures between two consecutive stone blocks. b) The lower image shows the absence of at least one stone block.

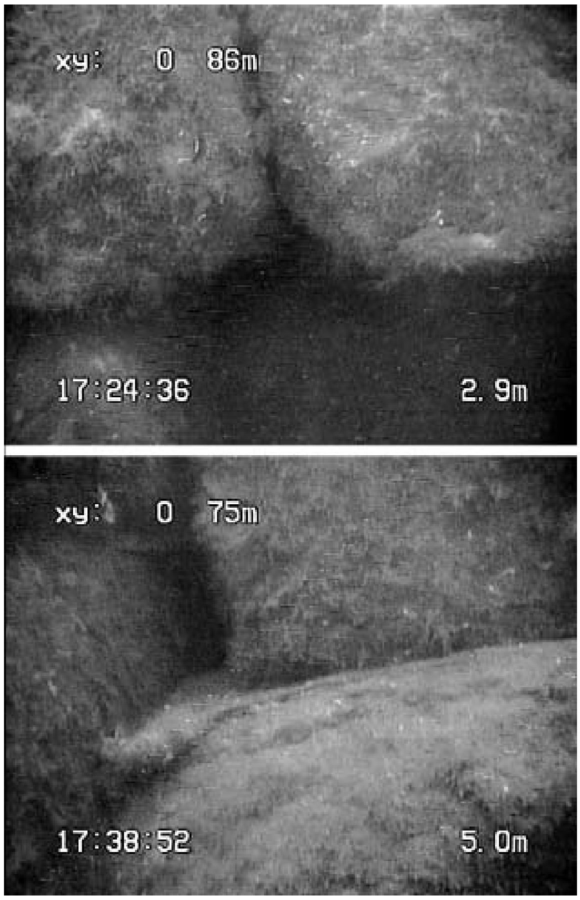

Fig. 5. Images captured by the vehicle. In both images we detect the absence of at least one stone block.

x and y position of the ROV (see on picture 3 the green squares). However, in this mission there was no need for absolute position measuring on both DOFs. Therefore, we decided to deploy the transponders close to the wall (see on picture 3 the dark blue squares) to operate on the base line. This way we are able to get a better accuracy in that degree of freedom. After installing the transponders, we measure their positions and load this data into the vehicle navigation software.

3.2 Mission execution

There are two modes of operation: tele-operation and tele-programming. In the first one, the operator has the ability to pilot the vehicle with a joystick. In the second one, the operator fills in the parameters of a template maneuver and commands its autonomous execution.

In each of them there is some difficulties in piloting the vehicle due to its asymmetries. This suggests the modelling of all thrusters and the design of a TAL system. That will be addressed in the following two sections.

When we started the inspection we realized that the visibility was quite poor due to pollution. This lack of visibility forced the operator to reduce the distance between the vehicle and the wall. Some images captured by the ROV during the inspection process are presented in figures 4 and 5. These pictures also show the amount of marine growth on the wall. Notice that the display superimposes the vehicle position and current time on the image. In figure 4 a) we can observe a fissure between two consecutive blocks. In the figures 4 b) and 5 we realize that the darker part corresponds to missing blocks.

Including preparation and setup this mission took less than two days. One of the innovative aspects of the operation of the IES system is that it allows for the specialists to actually pilot the ROV. This allows them to study in detail and in real-time the features of the images taken by the ROV.

4. THRUSTER IDENTIFICATION

4.1 The complete thruster model

A thruster is composed of a motor (in our case a DC motor) and a propeller (Fossen, 1991; Gomes,

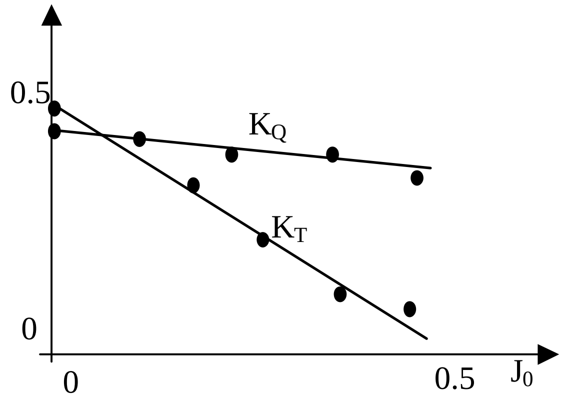

Fig. 6. Propeller parameters

2002; Lewis, 1989). The motor equations are very well known and therefore we skip their presentation. The propeller model is a bit difficult to achieve. Some of the difficulties are:

- the separation of the drag forces of the vehicle and the propeller thrust;
- complex hydrodynamic behaviors like vortex shedding on the propeller blades, unmodelled blades, duct effects.

The forces (F) and moments (Q) produced by the propeller depend on both the vehicle and the propeller velocities. A first order model approximation is usually used

$$T = \rho D^4 K_T(J_0)\,|n|\,n \qquad (1)$$
$$Q = \rho D^5 K_T(J_0)\,|n|\,n \qquad (2)$$

where ρ is the water density, D the propeller diameter, n the propeller revolution, $K_T(J_0)$ the propeller coefficient and J_0 the advance number. The advance number is given by

$$J_0 = \frac{V_A}{nD} \qquad (3)$$

where V_A is the advance speed.

The advance speed is the speed of the water going into the propeller. Experiments are required to obtain the model parameters. The objective of these experiments is to collect several (J_0, T) and (J_0, Q) pairs. These pairs can be converted in (J_0, K_T) and (J_0, K_Q) pairs with the following expressions.

$$K_T = \frac{T}{\rho D^4\,|n|\,n} \quad K_Q = \frac{Q}{\rho D^5\,|n|\,n} \qquad (4)$$

These pairs can be represented in a graphic, like the one presented in figure 6. Once we have a large number of pairs, it is possible to get a linear regression which leads to

$$K_T = \alpha_1 + \alpha_2 J_0 \qquad (5)$$
$$K_Q = \beta_1 + \beta_2 J_0 \qquad (6)$$

The final forces and moments are given by

Thruster\Param	k_f	k_b	n_{0f}	n_{0b}
F_1	2.4E-6	2.5E-6	50	50
F_2	2.9E-6	2.2E-6	60	70
F_L	5.3E-6	5.3E-6	60	60
F_V	n/a	n/a	n/a	n/a

Table 1. Identified thruster parameters

$$T = \rho D^4 (\alpha_1 + \alpha_2 J_0)\,|n|\,n \qquad (7)$$
$$Q = \rho D^5 (\beta_1 + \beta_2 J_0)\,|n|\,n. \qquad (8)$$

4.2 Experimentation and parameter identification

We ran a series of experiments in a small tank in our lab for parameter identification. We lacked a full-fledged experimental set-up and we had to rely on some simplifications, and also on engineering judgement. First, it was impossible to measure the forces produced by each thruster while it moves with constant speed. Therefore we decided to measure all the thruster forces only on stationary conditions. Second, it was impossible to measure the propeller moment (Q). The only way to achieve this goal was to measure the motor current and estimate its torque, but we didn't have that measurement. Furthermore, the propeller moment is not very significant in the vehicle motion, and so its model was not considered.

Another important issue, is that some propellers are asymmetrical and two different models (one on each rotation direction) had to be considered.

The last important aspect regards thruster force dead zone. This dead zone is induced by the motor dead zone. Additionally there is a very low thrust force at low propeller revolutions. To achieve a more real model, this nonlinear part had be included.

Having all this issues in mind, we got the simplified model (Cassia *et al.*, 2000):

$$T = \begin{cases} k_f (n - n_{0f})^2 & n > n_{0f} \\ 0 & n_{0b} < n < n_{0f} \\ -k_b (n + n_{0b})^2 & n < n_{0b} \end{cases} \qquad (9)$$

where k_f and k_b are the thrust constant in forward and reverse directions respectively and n_{0f} and n_{0b} are the propeller revolutions (rpm) that correspond to the boundary between zero thrust and some thrust in forward and reverse directions.

In order to collect data, each one of the thrusters was moored with a cable. The cable mounted a strain gauge to measure the thruster force. For different propeller revolutions the produced thrust was registered. The same experience was performed with the thruster in the opposite direction.

Using an identification procedure based on the least square method we got the parameters presented in table 1.

To guarantee that a desired force is correctly generated by the thruster is necessary to have feedback on the motor speed. For instance imagine that the ROV lights are powered up. Since the electric resistance of the umbilical cable and the power supply are not null, this means that there will be a voltage drop in the motor input. Therefore the motor velocity will decrease and so will the thrust. That's why the motor velocity feedback is important. The controllers used are PI type and are running with a sampling frequency of 40Hz.

5. THRUST ALLOCATION LOGIC

In this section we want to decouple the principal motions of the vehicle with resource to thruster actuation. For instance suppose that we want the vehicle to move only in the forward direction, the objective is to calculate which forces must be applied to the vehicle so that the it moves only in that direction. To do so, it is necessary to analyze the force system acting upon the vehicle. We are only concerned with constant speed because it is easier to achieve our goals since the acceleration terms are not present.

5.1 Forces to be balanced

The forces that are applied to the vehicle while it moves with constant speed are the drag and the thruster forces. As we seen before, the vehicle has 4 elemental motions: forward, lateral, vertical and rotation. The vertical and rotation motion have no problem since the vehicle is balanced. The problematic motions are the forward and the lateral ones, specially the last one. The main idea is to calculate where is the application point of the drag force and measure the truster center in order to compute the moment arm for rotation in yaw.

The physical arrangement of the ROV is not symmetric due to design considerations and tradeoffs (refer to the lateral view on fig 7). Obviously, this means that the vehicle drag force is not positioned in its center, but somewhere else. The vehicle was divided in 6 different pieces ($P_1..P_6$). For each piece a drag force was obtained by using:

$$F_{d_i} = -\frac{1}{2}\rho C_{D_i} A_i v\,|v| \qquad (10)$$

where v is the vehicle velocity, A_i the area of the piece, ρ the water density and C_D the drag coefficient. After performing all necessary calculations, we found where is the application point of the main lateral drag force. The distance between this point and the lateral thruster position gives

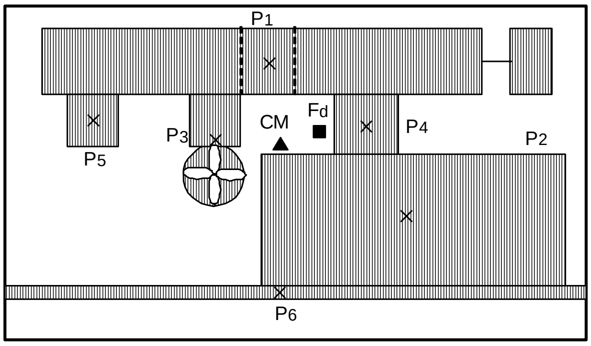

Fig. 7. Contributions of the drag of each physical element for the overall lateral drag force

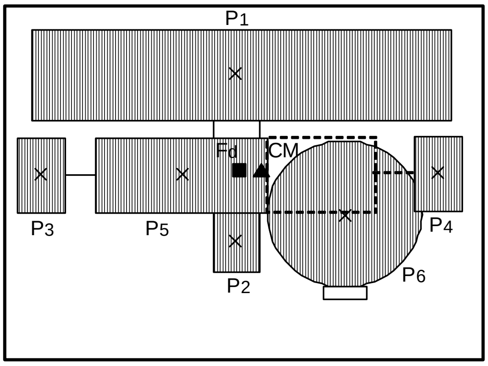

Fig. 8. Contributions of the drag of each physical element for the overall forward drag force

the moment arm that forces the vehicle to rotate in yaw.

Doing exactly the same for the longitudinal motion of the vehicle, we find the moment arm that forces the vehicle to rotate in yaw (fig 8).

Fig 9 displays all the forces. When the vehicle moves with constant speed, F_d has the same value of the lateral thruster force but opposite sign. Writing the equations of forces X, Y, Z and moment N as a function of thruster forces, we get:

$$\tau = BF$$

$$\tau = \begin{bmatrix} X \\ Y \\ Z \\ N \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -B_1 & B_2 & B_L + B_d & 0 \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_L \\ F_V \end{bmatrix}$$

where B_1, B_2, B_L and B_d represents the moment arm of each force with respect to the Center of Mass (CM). The forces to be applied to the thrusters can be easily computed by $F = B^{-1}\tau$. The τ forces are provided by the ROV trajectory generation system.

5.2 Results

To validate the thrust Allocation Logic two different experiments were performed in the USTL tank; with and without TAL. The basic experiment consists in actuating the vehicle laterally.

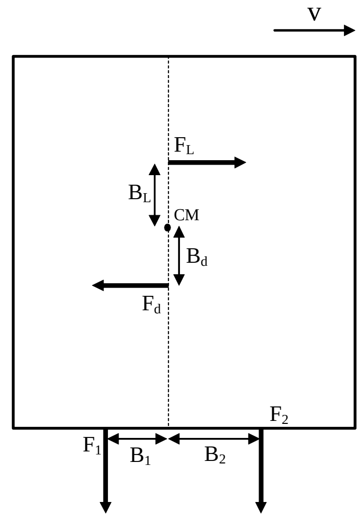

Fig. 9. Forces applied in the vehicle while moving in constant speed

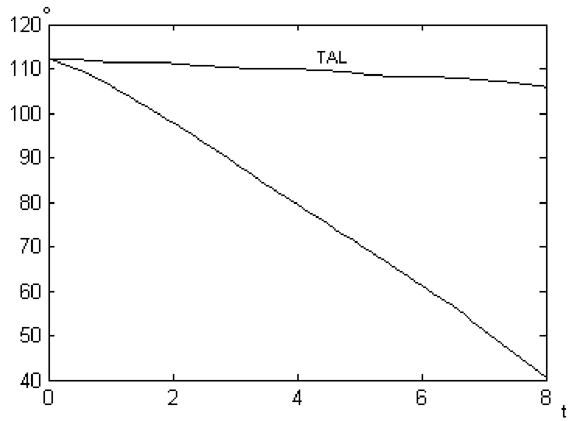

Fig. 10. Real data of the behave of the ROV in terms of yaw drift with and without TAL

The experimental data is presented in figure 10. Without the TAL system there is a drift in the orientation of 70 degrees in about 8 seconds due to the asymmetries of the vehicle. With the TAL system on, we can observe almost the preservation of the orientation in open loop (7 degree drift). It is not perfect, but under feedback, the orientation will improve significantly.

6. CONCLUSIONS

This paper discusses the problem of improving control performance of a Remotely Operated Vehicle with thruster modelling and identification and with Thrust Allocation Logic. A study of the forces acting upon the ROV was performed in order to have a good model of the system. The TAL strategy was designed to improve control performance. For validation purposes some experiments were also performed at the USTL facilities. The results of those experiments allowed us to conclude that the TAL strategy is adequate and therefore this method proved to be a good alternative to the vehicle physical redesign.

In future we are planning to instal additional thrusters so that the vehicle becomes over-actuated (Webster and Sousa, 1999). By that time we will be able to put thrusters operating in differential mode to guarantee faster positioning. This is achieved because thrusters are already working when the force is needed. Another issue to be addressed in future concerns modelling the acceleration parameters.

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