# AUTOMATIC CONTROL OF A LOW-COST COMMERCIAL ROV

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## Abstsract

In this paper the development of a low level control system, on a small, low cost, Remotely Operated underwater Vehicles (ROV's), so to facilitate their use and to extend their range of application is described. The results achieved ease the task of the operators and enhance the performances of the ROV as a robotic device allowing to cope satisfactorily with a number of basic problems, like station and attitude keeping and trajectory following, without requiring direct human intervention. Serviceability of the vehicle is, in this way, considerably increased.

## Introduction

In many marine activities, including scientific research and commercial exploitation of oceanic resources, Remotely Operated Vehicles (ROVs) are one of the most important tools. Recent advances in robotics and control theory caused improvements in ROVs' capabilities, but still, the increasing technological demands, the need of reducing the costs of the underwater activities and safety requirements call for robotics systems with enhanced performances in terms of guidance capability and autonomy.

Manual guidance and control of underwater vehicles, like ROVs is in general a demanding task, that requires specially trained operators and the efficiency and effectiveness of the current methods are limited by the ability of the human operators to guide the ROV, their ability to interpret on-line environmental data and, given the monotonous nature of tasks, by their concentration capability. A great help comes, at this regard, from the development of automatic systems that, allowing both on-line processing of sensory data and implementation of automatic control procedures, may reduce the burden imposed to human operators. A system of this kind has been constructed for guidance and control of a small work-class ROV (DOE Phantom S2) allowing a PC to take care of low and mid level control tasks.

In this process of endowing the system with autonomous and active behaviors, a typical application namely underwater pipeline's inspections (see [2], [4], [5], [6], [7], [14], [19] and [20]), has been considered. The specific problem at issue consisted in assisting, or possibly substituting partially, the human operator in the guidance of the vehicle during typical inspection missions. This required acting on the guidance level developing an automatic visual feedback guidance system and on the control level designing a suitable thruster controller.

The paper is organized as follow: preliminarily the ROV original configuration and its standard operative procedures system are illustrated; subsequently, the proposed hierarchical NGC architectures is discussed. System enhancements both at the guidance level and at the control level are described in the two following sections. Concluding remarks on the achieved results are reported at the end of the paper.

## Original System Configuration

The ROV, in its originally configuration, is controlled manually by means of two joysticks on the console. In this way, acting on the joysticks, direction and speed of the vehicle can be set. Four thrusters (two horizontal ones and two vertran ones) provide for the vehicle motion by actuating four degrees of freedom.

The two joysticks on the console provide separately for the motion in the horizontal plane (forward and reverse direction, left and right) and in the vertical plane (up and down direction, left and right).

In the purchased configuration the Phantom S2 was equipped with a magnetic compass, a depth sensor and a CCD camera with two halogen lamps. Lectures from the first two sensors are displayed on the console while images from the CCD camera can be viewed on an additional monitor.

The scheme of Figure 1a summarizes the original NGC hierarchical structure [11] of the ROV system. The human user, in this standard ROV operative modality, acts at all the three levels. After assigning the global task, the operator generates the motion directions and intensity references which are necessary to maintain the vehicle in the desired track. At the low level, he/she closes the loop with the PWM driver so to command the thrusters.

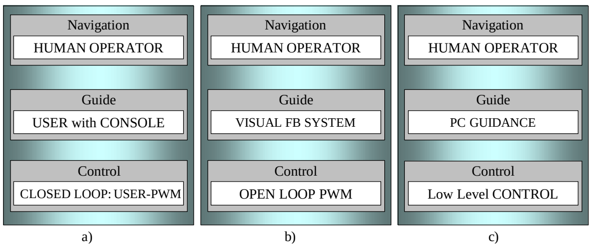


Figure 1:ROV hierarchical functional scheme: a) original configuration, b) and c) accomplished modifications

## Automatic control system configuration

The guidance task, when performing pipeline survey, can be summarized as keeping the ROV above the pipeline, aligned with it at an assigned vertical distance. The operator thus, monitoring the images on the screen and the compass and depth sensor data, has to adjust the vehicle track acting on the two joysticks.

In order to implement automatic control and guidance strategies, the guidance system of the ROV has been redesigned, by introducing a PC (actually a PentiumIII 866MHz) in the loop between the human operator and the vehicle system.

Besides, the proprioceptive sensor system has been enhanced thus being able to close the control loops. A strapped down inertial platform [1], [9], [10], [11], [15], [17], [18], characterized by low cost and low power consumption, has been mounted on the vehicle. In addition, two optical sensors have been mounted on the thrusters so to gain information on the actual shaft rotational speed during navigation. This information is essential in the identification process of the ROV thrusters' operative characteristics, as it will be clarified in the following. A suitable processing board has been developed for a correct and noise free interpretation of the signal coming from the optical sensors.

Given the specific task at study, that is supporting the operator during pipeline survey, it was necessary to gather environment awareness, namely information on the ROV/pipeline relative position. Exteroceptive information coming from the CCD camera has thus been processed so to extract, from each image frame, the position of the pipe. A visual feedback controller has been developed as described in the following section, which provides to keep the vehicle on track.

After the insertion of a PC, the human operator could be "by-passed" in the control of the ROV. Two main steps have characterized the development process of the automatic control system. Firstly, the ROV motion control has been simply achieved emulating his/her actions on the joystick, sending suitable signals to a port that was originally present on the console. In this way, the possible motion commands were the same actuated through the two joysticks, that is it was not possible to act directly on each thruster but only commanding the motion direction and speed. A combination of surge and yaw motion was obtained by acting on the couple of horizontal thrusters through the left joystick board, while a combination of heave and sway motion was obtained by acting on the couple of vertrans thrusters through the right joystick board.

The new NCG hierarchical structure as resulted from this first modifications step is summarized in Figure 1b

Experimentally was noticed that commanding a straight surge motion, the vehicle would evidence a yaw motion.

Slight difference were noticed between the propeller profiles of the two horizontal thrusters that, however, seemed not to justify the intensity of the detected yaw motion component. This motivated a supplementary study on the joystick-thruster characteristic. Figures 2 and 3 show the shaft response to surge and yaw commands in terms of Revolution Per Second (RPS) of the left and right thruster, respectively.

This study confirmed that there was a significant asymmetry on the achieved rotational speed and motivated further modifications of the system.

Step two in the development process of the automatic control system, essentially consisted in the design and implementation of a close loop thrusters control system at the low level of the NGC structure.

This required the analysis of the original actuation system, the identification of the model of some

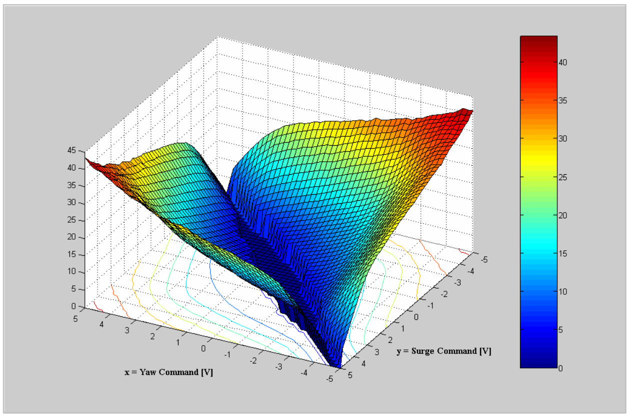


Figure 2: Left motor steady state identification via joystick commands.

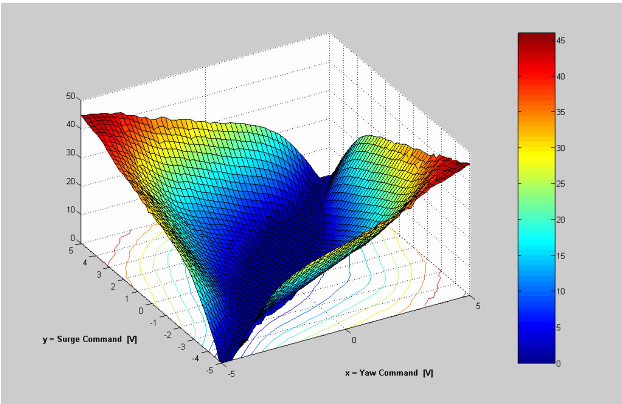


Figure 3: Right motor steady state identification via joystick commands.

components and the design of new ones, as it be described in the following.

Figure 1c depicts the final NGC hierarchical structure of the ROV system.

## Visual feedback control

The task of the automatic control is that of correcting the ROV position according to the imposed constraints. Basically, this is to be achieved by detecting the pipe in video-images and by reconstructing the relative position of the ROV, from position, orientation and size of the pipe in the image plane. The visual feedback guidance system, whose scheme is depicted in Figure 4, acts by acquiring low level sensory data, by performing a high level data processing and interpretation, by computing a corrective action and finally by sending a command to

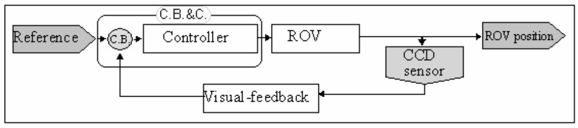


Figure 4: Block diagram for the Visual feedback Control system.

the control level. Raw data consist of RGB signals generated by a standard CCD camera. Suitable numerical algorithms, implemented by the PC in the loop, have been developed so to perform high level data processing, data interpretation, and control action computation. The system consists essentially of two main parts, the image processor (IP), that determines the actual ROV's position from the acquired image sequence, the comparing block and the controller (CB&CTRL), which implements the feedback strategy.

The developed visual feedback controller (see [19] for further details) corrects for variation on the relative depth position (proximity control) and on the lateral displacement (sway control). No corrective action for variation on the relative orientation ROV/pipe has been supplied at that stage of system development. For this reason, the effects of the unexpected asymmetry of the two thrusters, mentioned in the previous section, could be clearly noticed. In the trial showed in Figure 5, the guidance algorithm could successfully conduct the ROV along the pipe direction maintaining it in the center of the image. However, due to the presence of a yaw component, the pipe resulted not to be vertically aligned, as the image frames sequence clearly show.

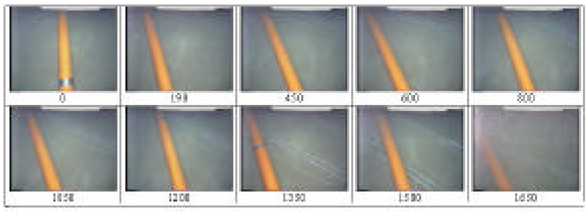

Figure 5: Image frames sequence during pipeline following experiment

## Low level thrusters control

The implementation of the visual feedback guidance controller, does not guarantee the achievement of the desired goal if the performances of the low thrust controller are not sufficiently good, as seen in the previous section.

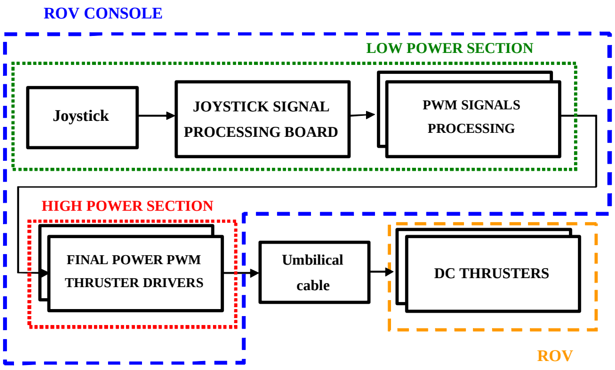


Figure 6: Actuation system block diagram.

This required investigating on the existing actuation system, the scheme of which is summarized in Figure 6.

As a consequence of this study, the low power driving section has been completely redesigned. In fact, in the original design, many non linear blocks were present. In particular, the sensibility of the joysticks was made lower around the equilibrium point accordingly to the human operator wrist sensibility. This behavior is useful in the operator-modality but inadequate in the PC guide configuration.

Furthermore, a decoupling of the thruster actuations has been performed so to have the possibility to act directly to each final power PWM driver. In the final design, as Figure 7 shows, the high power driving block and corresponding thruster has been kept unchanged and needed to be identified (dotted block in Figure 7).

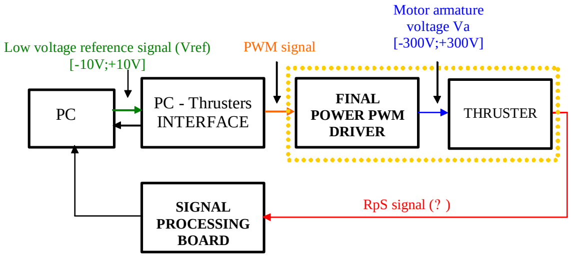


Figure 7: Block diagram for the final actuation system.

## PWM Driver Identification

A black box input-output identification procedure [12] has been adopted to model the behavior of the final power PWM driver. Figure 8 shows the computed armature voltage-reference voltage (Va-Vref)

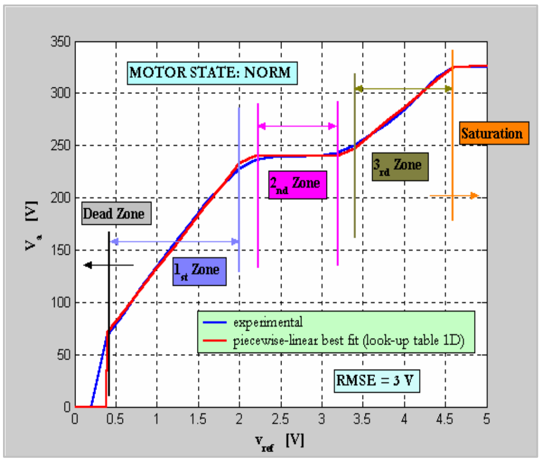


Figure 8: Static characteristic Va-Vref for left thruster.

characteristic of this block, with the adopted piece-wise linear approximation. Five different operational zones have been identified: a *dead-zone* where the thruster is not activated receiving a null input voltage, a *first zone* characterized by a linear outline, a *plateau* distinguishable for the constant response to variation of the Vref, a *third* linear *zone*, and finally a *saturation* region. LS Best-Fitting techniques [12] have been implemented to optimally identify the parameters of each zone.

## Thrusters Model Identification

A different approach has been adopted for the identification of the thrusters block. A mathematical model of the motor has been considered and parametric identification techniques have been applied. In accordance with the electric motor theory, the adopted model, in the Laplace domain, is summarized in the following expressions:

$$? (s) ? W_{V_a}(s) ?V_a(s) \; ? \; W_{C_L}(s) ?C_L(s), \qquad (1)$$

$$W_{Va}(s) ? \frac{K_m}{J_t L_a s^2 ? (L_a F_V ? R_a J_t)s ? R_a F_V ? K_E K_m}$$

$$W_{C_L}(s) ? \frac{R_a ? sL_a}{J_t L_a s^2 ? (L_a F_V ? R_a J_t)s ? R_a F_V ? K_E K_m}$$

where O(s) is the shaft angular rate, $V_a$ is the armature voltage, $C_L$ is the external load torque. The transfer functions $W_{Va}$ and $W_{CL}$ are given by:

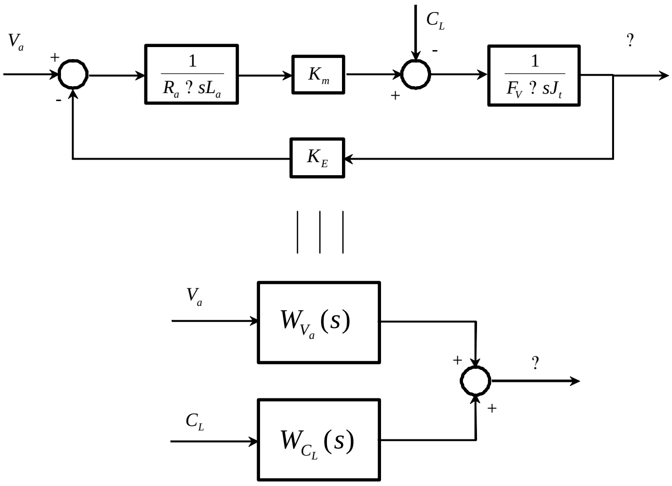


Figure 9: DC motor block diagram

$$W_{Va}(s) ? \frac{K_m}{J_t L_a s^2 ? (L_a F_V ? R_a J_t)s ? R_a F_V ? K_E K_m} \quad (2)$$

$$W_{C_L}(s) ? \frac{R_a ? sL_a}{J_t L_a s^2 ? (L_a F_V ? R_a J_t)s ? R_a F_V ? K_E K_m} \quad (3)$$

The block diagram of the DC-motor model is depicted in Figure 9

Expression (2) and (3) above can be reformulated evidencing the presence of two poles, $t_m$ and $t_e$, which model the mechanical and the electrical characteristic of the motor, respectively.

$$W_{V_a}(s) ? \frac{G_{V_a}}{?1 ? s?_m ??1 ? s?_e ?} \quad (4)$$

$$W_{C_L}(s) ? \frac{G_{C_L}}{?1 ? s?_m ??1 ? s?_e ?}. \quad (5)$$

where $G_{Va}$ and $G_{CL}$ are the static gains.

In order to identify the parameters in equations (2) and (3) different experiments set-up have been considered.

The parameters related to the steady state ($G_{Va}$, $G_{CL}$, $R_a$, $K_m$, $F_V$) have been computed developing specific test bed experiments on unloaded motors.

Given the model working conditions, and considering that in the actual system the armature inductance $L_a$ is very small (about 5 mH), the electrical pole can be assumed to be negligible (1/ $t_e=R_a/L_a$?630 Hz). Thus, the dynamic behavior of the motor can be assumed to depend essentially on the mechanical pole.

Suitable laboratory and tank trials were carried out in order to gather data for the estimation of $t_m$ , $J_t$ and steady state values for $C_L$. In the identification process, the dynamic effects of the signal processing board [13] (see the block scheme in Figure 7) developed for the shaft speed sensor, have to be taken into account.

In Table 1 the estimated parameters values have been reported.

| Physics Parameters | Symbol | Value | | Measurement Unit |
|---|---|---|---|---|
| | | Left Thruster | Right Thruster | |
| Static Gain $V_a$ - O | $G_{V_a}$ | 1.0713 | 1.1058 | [rad $s^{-1}$ $V^{-1}$] |
| Static Gain $C_L$ - O | $G_{C_L}$ | 23.3187 | 23.4017 | [rad $s^{-1}$ $N^{-1}m^{-1}$] |
| Armature Resistance | $R_a$ | 20 | 19 | [? ] |
| Armature Inductance | $L_a$ | 5 | 5 | [mH] |
| Induced Voltage Gain | $K_E$ | 0.9188 | 0.8978 | [V $rad^{-1}$ s] |
| Motor Torque Gain | $K_m$ | 0.9188 | 0.8978 | [N m $A^{-1}$] |
| Moment of Inertia | $J_t$ | 5.5 $10^{-3}$ | 5.2 $10^{-3}$ | [N m $rad^{-1}$ $s^2$] |
| Friction Coefficient | $F_V$ | 6.7270 $10^{-4}$ | 2.8949 $10^{-4}$ | [N m $rad^{-1}$ s] |
| Mechanical Time Constant | $?_m$ | 127.21 | 121.19 | [ms] |

Table 1

## Model validation

To validate data the following Simulink™ scheme has been adopted

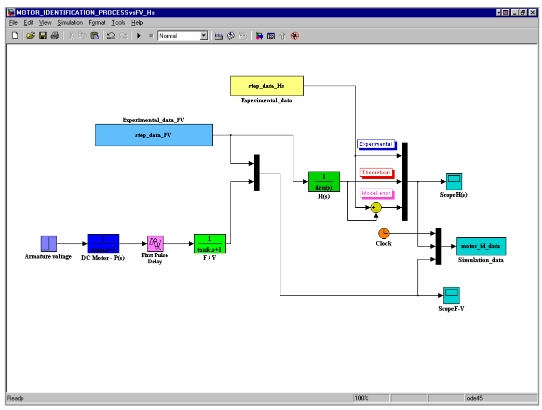

Figure 10: Smulink diagram of the validation system.

The P(s) (dark-blue) block receives as input a step-wise constant function representing the armature voltage.

The (pink) delay block has been introduced so to emulate the data acquisition board performance.

The green blocks represents the Frequency-Voltage signal processing system of the shaft speed sensor.

As Figure 11 shows, theoretical and experimental data are in good agreement and the model can be accepted.

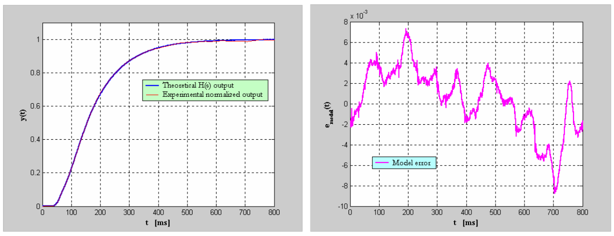


Figure 11: Validation test result. a) Experimental normalized output (red curve) and theoretical output (blu curve); b) Model error.

## Conclusions

The process of endowing an ROV with automatic navigation capabilities has been described.

Implementation of the system required the realization of a simple interface and the insertion of a PC in the loop actuating a control modality based on a PC. The human operator, in this configuration, plays the role of supervisor, acquired data evaluator, and mission decision maker.

The low level thrust control has been redesigned in order to control the ROV motion with a better accuracy. In fact, if the human operator can easily adapt to compensate for asymmetries and non linearities, the design a control system capable to cope with them would be inconveniently complicated. Moreover, decoupling of the actuations of each single thruster has been achieved thus gaining more control flexibility.

Finally, identification of the thrusters model and of their final power PWM drivers have been performed.

Laboratory tests have successfully proven the effectiveness of the proposed system

The implementation of different controllers [3], [16], based on advanced techniques (LQ, fuzzy, robust control) are currently on study, and infield trials are scheduled for testing the overall system performances as well as its reliability and safety.

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