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AN AUTOMATIC GUIDANCE SYSTEM FOR A SMALL WORK-CLASS ROV

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Abstract: In this paper, the design of the overall architecture and the development of specific components of a supervised, automatic system for guidance of an ROV are described. Basically, automation is achieved by inserting a PC, equipped with A/D-D/A boards, in the operator/ROV loop. In this way, the original configuration of the ROV manual guidance system is substituted by a more versatile, user-friendly and powerful PC-based configuration. The paper describes the basic features of the realized system, that, by allowing both on-line processing of sensory data and implementation of automatic control procedures, enhances the performances of the ROV as a robotic tools. *Copyright©2002IFAC*

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1 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 their guidance and operating systems are characterized by a low level of automation, both in elementary control aspects and in higher decisional and data handling aspects. As a consequence, guidance and control of work-class ROVs is a demanding task, that requires specially trained operators and a high level of concentration.

In this paper, we describe the design of the overall architecture of a supervised, automatic system for the guidance of an ROV, that is conceived to facilitate the task of the operators and to enhance the performances of the ROV as a robotic device. In particular, we discuss the characteristics of the systems by analyzing its specific hardware and software components and, as an example of the system capabilities, we describe the implementation of a visual-feedback guidance strategy on an ROV.

Basically, the system is realized by inserting a PC in the operator/ROV loop. This configuration, that will be called PC-based (control) configuration, allows us to achieve a first level of automation. In particular, signals from and to all system components, i.e. on-board sensors and thrusters or other actuators, are processed by or through the PC. In particular, this allows to implement automatic low level control strategies for performing elementary tasks, releasing the operators, e.g., from the necessity of controlling position or attitude of the ROV during the execution of more complex tasks, as well as higher level guidance strategies. Moreover, sensory data can be processed on-line both at low level, by means of filtering, aggregation or fusion techniques, and at high level, by means of symbolic reasoning techniques, so to provide structured information to the operator and to increase his situation awareness. The PC-based configuration makes also possible to record simultaneously a large amount of navigation or mission data, which in this way become available for off-line processing.

Interaction with the operator is realized with the aid of a virtual console. When specific tasks are performed in automatic mode, the operator acts as a supervisor. His presence, in particular, enables the system to overcome difficulties due to sensor limitations and to the large variability of the natural environment, which exceed its level of artificial intelligence. In addition, the operator plays the role of acquired data evaluator and of mission decision-maker. In all the cases of inadequacy or failure of the automatic procedures, the control is shifted quickly and safely to the operator.

The key aspects of the system in this configuration are represented by the capability of exchanging information at high symbolic level with the supervisors, of reasoning about data and of exhibiting autonomous behaviors in order to facilitate and support the operator's task.

In order to provide an example of how the system potentialities can be exploited, we describe the implementation of an automatic guidance strategy based on visual feedback techniques. The mission scenario we consider is related to the survey of an underwater pipeline. Visual inspection of the pipe is, in this case, one of the basic task to be accomplished (see Conte, *et al.*, 1995; Conte and Zanoli., 1997; Conte *et al.*, 1994; Iovenitti *et al.*, 1994) and, therefore, this motivates the choice of vision in mission control (see Conte *et al.*, 1996; Davis, 1990; Nguyen *et al.*, 1988; Santos and Sentiero, 1994; Tascini *et al.*, 1996; Zingaretti and Zanoli, 1998). The performances and the efficiency of the implemented guidance strategy are described and discussed on the basis of emulation experiments and field tests, that, as a by-product, validate the developed PC-based configuration in governing the ROV.

2 STRUCTURE AND MAIN FEATURES OF THE SYSTEM

The Remotely Operated Vehicle we consider is a Phantom S2 made by Deep Ocean Engineering. The vehicle's standard sensory equipment consists of a magnetic compass, a depth sensor and a CCD camera with two halogen lamps. A strap-down inertial platform (Inertial Measurement Unit or IMU) has been mounted on the ROV, so to measure linear accelerations and angular velocity along three orthogonal axis. Four thrusters (two horizontal ones and two vertran ones) provide for the vehicle motion by actuating four degrees of freedom. In its original configuration, the ROV is manually governed through a console, endowed with joysticks and simple liquid crystal displays, by a human operator. Such configuration has been modified, and the guidance system of the ROV has been redesigned accordingly, by introducing a PC (Pentium III 866 MHz) in the loop between the human operator and the vehicle.

The hardware architecture of the PC-based configuration employs standard, low cost D/A-A/D boards. The physical connection between the PC and the ROV is realized through the external input and output ports of the console. This solution keeps always available the manual guidance configuration in case of failure of the PC-based one. Information coming from on-board sensors can be displayed on the PC monitor and command inputs can be given through the PC input devices. The man/machine interface is characterized by a versatile Virtual Console, easily re-configurable to satisfy specific requirements, through which the operator interacts with the system.

The interconnection of all the single parts of the system has required the development of suitable software. The emphasis has been put on the realization of a prototypal system which can guarantee feasibility and whose performances can be evaluated in an easy and rapid way. This motivates the choice of working mainly in the Labview software environment, that allows the use of a graphical programming language and provides a large library of programs for handling data acquisition and analysis and for implementing control schemes. The possibility of splitting into parts the execution of complex programs simplifies, in addition, the debugging process.

It should be remarked that, at the present stage of development, the system does not work in real-time and lacks portability. However, both these limitations are, for the moment, of little concern, as they can be removed without difficulty by moving to a different software environment, based on a real-time operating system, at a later stage.

Control strategies can be implemented manually, by using the PC input devices and the virtual console to assign appropriate values to the control variables. Alternatively, automatic control strategies can be selected from a library and the system can be put in automatic mode. Station keeping or depth regulation (see Conte and Serrani, 1998; Jin *et al.*,1996; Zanoli and Conte., 2000) are examples of low level control tasks that are executable in automatic mode by letting the PC compute a suitable error signal from sensory data and generate appropriate input to the thrusters. The visual feedback guidance strategy described in Section 3 is an example of higher level control strategy, since the computation of the error signal requires a previous image processing at symbolic level. The computational burden is quite different in the various cases, but it remains within the capabilities of the employed PC.

Filtering, aggregation and fusion of sensory data can be performed on-line in the PC-based configuration, producing an enriched information on the surrounding environment (see Borenstein, *et al.*, 1996) and on the system performances and enhancing the operator's situation awareness. In particular, inertial data coming from the IMU are processed and used to display the ROV attitude, with respect to roll and pitch angle, by means of an artificial horizon. Augmented reality can, in addition, be used for adding content to the representation of the environment obtained by the sensors. This possibility can be exploited, for instance, for pointing out to the operator the contours of objects that specific image processing algorithms may detect in camera images. When automatic guidance strategy based on visual feedback techniques, like the one described in the next Section, are active, augmented reality helps the operator to supervise the system performances and to accomplish more easily tasks like visual inspection of submerged structures.

Finally, the possibility of recording synchronized mission data offered by the PC-based configuration and the consequent possibility of post-processing data result to be useful for achieving a better knowledge of the overall system behavior. As an application, identification of the ROV dynamics has been performed. Basic experiments for collecting data consisted in applying suitable thrusts, corresponding to a given control voltage for each thruster motor, and measuring the resulting ROV linear accelerations and angular velocities (see (Conti, 2002)).
Details of the subsystems which are integrated into the PC-based guidance system are given in the following subsections.

2.1 The Virtual Console

The Virtual Console is organized into several, different zones, according to specific functions and characteristics, as described in Figure 1. The Thruster Command Area (Figure 2) contains a menu to select the power range for the thrusters (Low, Normal, Boost) and virtual devices (sliders) which substitute the joysticks of the console for assigning the desired thrust. Below these, a window shows the graph of the four input commands. Input values can be recorded in a file.

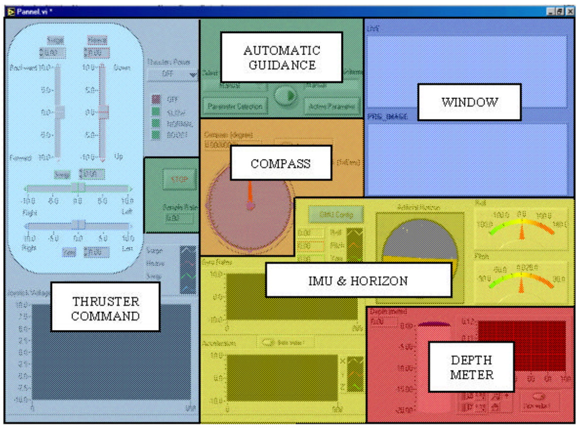


Figure 1. Virtual Console

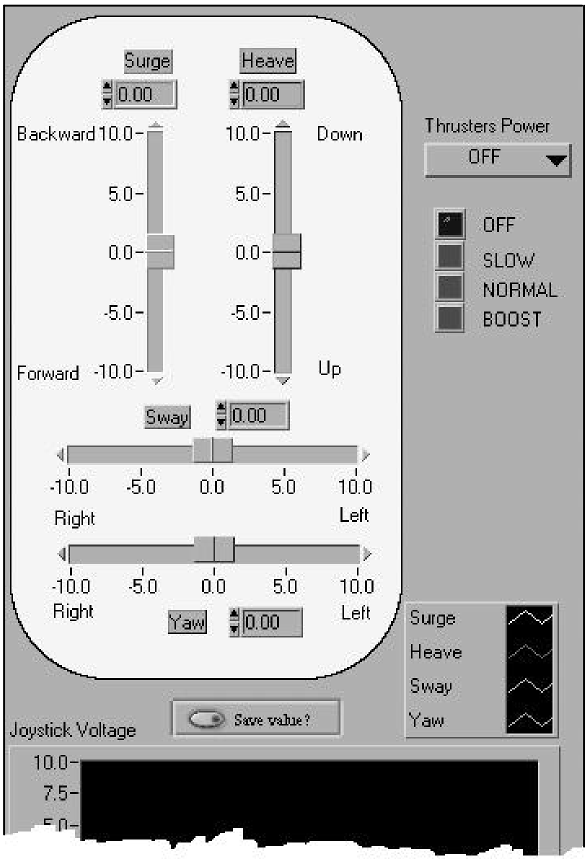
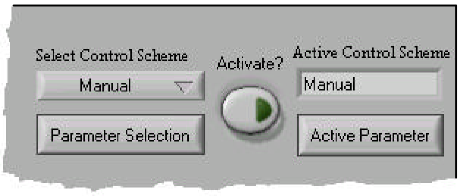


Figure 2. Thruster command area

The Automatic Guidance Area (Figure 3) contains drop-down menus to choose automatic control procedures from a library and to set the parameter of the controller. By clicking on a button, the operator can activate the chosen control procedure, disabling, at the same time, the sliders in the Thruster Command Area.

The Compass, Depth Meter, Artificial Horizon and IMU Areas (Figure 4) display, using different modality, the data coming from the various proprioceptive sensors and/or the information derived from them. Configuration parameters of the IMU are accessible from this area.

The Window Area is used for displaying either real or (partially) synthetic video images or acoustic images.


Select Control Scheme: Manual

Active Control Scheme: Manual

Figure 3. Automatic guidance area

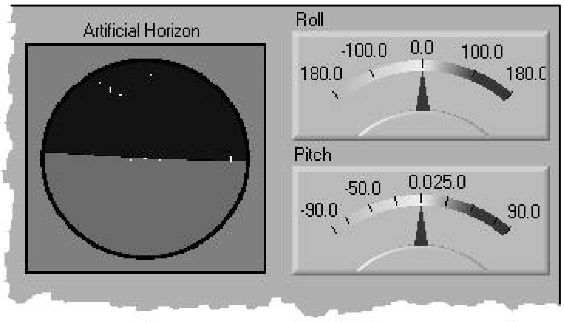


Figure 4. Artificial horizon

2.2 Low level control

The PC-based configuration offers the possibility to implement the control action either manually or by activation of an automatic procedure. In the first option, the operator can set the value of the control voltage acting on the devices of the virtual console by means of a mouse. Emulating the joysticks, these devices allow to assign elementary macro-commands and combinations of them, which cause activation of the thrusters in a proper way. A possible alternative mode, not implemented at the moment, consists in controlling the voltage of each single thruster. Acting on the virtual devices, the operator can regulate the control voltage, and hence the resulting thrust, more accurately than using the joysticks.

A library of automatic control procedures is accessible through a menu. After choosing the desired procedure, the operator can open a window to set the controller parameters. Activation of the control procedure follows by clicking on the proper button. Then, using the available signals from the sensors, the PC takes care to close possible feedback loops. Since all input and output signals are represented on the virtual console, the operator can monitor the action of the controller. When an automatic procedure is active, a second one (of the same kind of the active one, but with different control parameters, or of different kind) can be pre-set and then activated to substitute the current one. This procedure can be followed to go back to the manual control mode, that can also be recovered by pressing ESC on the PC keyboard. This latter is an emergency action that also sets to zero the control voltage to the thrusters.

2.3 Data Processing

The main computational effort that is required to the system in its present configuration concerns the processing of inertial measurements coming from the Inertial Measurement Unit. The IMU provides measures of linear accelerations and angular velocities which are internally filtered to reduce noise. Since the IMU is strapped-down to the ROV, the acceleration due to gravity must be detected and decoupled from the acceleration due to other causes in order to derive information about the vehicle motion (see Barshan and Durrant-Whyte, 1995; Kuritsky and Goldstein, 1990; Sukkarieh *et al.*,1995; Titterton and Westoet, 1997; Zanoli and Conte., 2001). This operation requires to initialize the IMU with the ROV at rest. During the initialization phase, the direction of the gravity vector, in a system of coordinates attached to the vehicle and having the origin in the center of gravity, is detected. Then, relative displacement of the gravity vector during the vehicle motion is computed by evaluating the vehicle attitude. Evaluation of the attitude is made by integrating over time the angular velocities, so to obtain the angular displacements. Once the direction of the gravity vector is known, its contribution be decoupled. The integration of the angular velocities and the other computations are accomplished by the PC and, as a result, the information about linear accelerations and vehicle attitude become available to the operator. In addition, this information can be used for closing feedback loops in automatic control procedures. Signal processing at various levels can also be performed on camera images. The CCD camera signal in standard PAL color and RGB format is acquired by an image acquisition board and made available for low level and high level, logical processing in automatic guidance and control procedures, like the one described in the next Section. Real images, as well as images resulting from processing, can be shown in the Window Zone of the virtual console or on additional monitors.

2.4 Data recording

The availability of recorded synchronized data gives the possibility of performing post-processing operations, which result useful in acquiring a better knowledge of the overall ROV performances.

In particular, this possibility has been exploited in collecting data for identifying models of the ROV dynamics and, then, validating them. Essentially, experimental data have provided identified models of the relationship between control voltage and the variable describing the resulting motion, assuming that the dynamics concerning the four degrees of freedom are decoupled. Motion has been determined from the inertial data coming from IMU. A further series of experiments has been performed in order to find the relationship between control voltage and thrust, so to obtain a more appropriate model for control purposes. Results are contained in (Conti, 2002).

In addition, the performances of the thrusters and of the various sensors can be monitored over long periods, helping in better understanding and possibly reducing the effects of malfuntioning and failures.

3 GUIDANCE SYSTEM

As mentioned above, the PC-based configuration has recently been used, in particular, for developing, implementing and testing a high level, automatic guidance procedure based on visual feedback. The control objective that is considered is that of moving the ROV along a pipe, laying on the sea bottom, at a constant distance from it. The pipe is visible and the employed control paradigm consists in controlling position, orientation and dimension of the pipe in the image plane of the camera, that is fixed to the ROV, by moving the vehicle. In order to generate the suitable control signal by feeding back an error signal, the system must first recognize the pipe in the acquired images and then compute its position, orientation and dimension.

The visual feedback system consists essentially of two subsystems: the image processor, that indirectly determines the ROV's position from the acquired image sequence, and the controller, which evaluates the error, computes the control and implements the feedback strategy. The image processor acts on the sequence of images acquired by the CCD camera and performs first a low level processing in order to reduce the effect of noise and to identify a group of points which may belong to the pipe's contours (candidate points). The contours search is initialized by the operator, who can indicate to the system the position of the contours in initial images. Then, the system chooses the best candidate points by using, at each step, the information about the location of the pipe obtained at the previous one and, in this way, it constructs the contours of the pipe in each image. The way in which the image processor and the controller work is described in more details in (Conte *et al.*, 2001).

In realizing the control strategy, it has been assumed, as working hypotheses, that the forward speed is constant, the rolling is negligible and the angle of pitch is constant. Furthermore, the vehicle motion equations, as well as the effects of the actuators actions, have been assumed to be decoupled. Two separate strategies, respectively for correcting sway and heave, have been adopted, by implementing in both cases a simple proportional control law. The output of the controller acts directly on the control voltage of the thrusters that actuate the corrective motion.

All operations related to the automatic guidance are performed by exploiting the computing capabilities of the PC that is at the basis of the guidance configuration

3.1 System Validation

To check the performances of the system, both field-tests and emulations have been made. In particular, to evaluate the efficacy of the visual feedback guidance system for what concern lateral motion, field tests have been carried on at the facility of the Institute of Naval Architecture (INSEAN) in Rome. The limited depth of the available test site did not allow a full test of the efficacy of the proximity control, that regulates the vertical distance from the pipe, but laboratory tests, emulating real situations, have been carried on.

In the pool experiment, a pipe (having a length of 8 meters and a diameter of 30 cm) was laid on the bottom the of a large pool and the ROV was intentionally given a lateral displacement of about 50 cm with respect to the reference position. Correction of the ROV position is achieved in about 20s. In a second experiment, the ROV started at one end of the pipe and moved along it by maintaining the desired relative position with respect to the pipe, in spite of intentional disturbances produced by pushing laterally the vehicle.

The performances of the system for the proximity control have been tested by emulating real condition with the use of recorded images. The PC-based configuration turns out to be instrumental also in this situation, since the experiment has been realized by connecting the video input of the system to the output of a VCR. Of course, in this situation, the control action is ineffective, since the position of the pipe in the image plane cannot be modified by moving the ROV. However, the control action can be measured and its possible effect can be evaluated with the aid of models of the ROV. Future experiments will take care of testing the system under this aspect.

From a qualitative point of view, the results of the experiment have shown that the system perform in a satisfactory way, guiding the ROV along the pipe with an accuracy that is comparable with that of a trained operator. Improvements are expected to come by implementing an enhanced low level thruster control and by exploiting the information on the ROV motion coming from the IMU in processing the images. Further accuracy in the corrective action can be achieved by using better models of the ROV and nonlinear, robust control strategies.

4 CONCLUSION

A small work-class ROV has been endowed with a supervised, automatic guidance system based on a PC. The PC-based configuration greatly simplifies the task of governing the ROV, by allowing the use of automatic procedures which enhance its autonomy, while increasing safety and reliability. Further exploitation of the capabilities of the system in survey and in data gathering mission will be the object of future work.

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