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UNION: UNderwater Intelligent Operation and Navigation

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N° 3038

November 1996

———————— THÈME 4 ————————

Rapport de recherche

UNION: UNderwater Intelligent Operation and Navigation

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Thème 4 — Simulation et optimisation
de systèmes complexes
Projet Icare

Abstract: The main goal of the UNION ESPRIT Basic Research Action is to develop methods for increasing the autonomy and intelligence of Underwater Remotely Operated Vehicles (ROV). The project focuses mainly on the development of coordinated control and sensing strategies for combined manipulator and vehicle systems. Both fundamental theories and methods for the design of these heterogeneous systems are investigated and concern: dynamic modeling and control for arm/base stabilization, use of sensory information (camera, sonars, lasers..) for pipeline inspection, navigation, programming, etc. Experimental and simulated results validated the theoretical developments. A complex canonical mission in the field of offshore Inspection Maintenance and Repair tasks was chosen to illustrate the integration of all the results.

The UNION project brings together seven European research groups working on underwater vehicles, robotics and intelligent sensing systems: (1)IFREMER, Subsea Robotics Laboratory (FR), (2) INRIA, SophiaAntipolis, ICARE Team (FR), (3) LIRMM-CNRS, Robotics Laboratory (FR), (4) UPC, Polytechnical University Barcelona (S), (5)LBM, Technical University Muenchen (D), (6)HWU, Heriot Watt University (UK), (7) Oxford University (UK).

Key-words: UNION, ESPRIT european project, underwater robotics, control, sensing, navigation, mission programming, combined manipulator and vehicle systems

(Résumé : tsvp)

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UNION: UNderwater Intelligent Operation and Navigation

Résumé : Le projet UNION financé par le programme de recherche européen ESPRIT, a pour objectif d'augmenter l'autonomie des véhicules sous-marins téléopérés (ROV ou Remotely Operated Vehicle dans la terminologie anglo-saxone). Des problèmes de modélisation dynamique et de commande pour la stabilisation du véhicule doté d'un bras manipulateur, d'utilisation d'informations capteurs (caméra, sonars, laser..) pour l'inspection de pipelines dans l'industrie offshore, de navigation, de programmation, etc. ont été traités. Des résultats en simulation et sur sites expérimentaux ont validé les développements théoriques réalisés. L'étude d'une mission canonique complexe d'inspection et de réparation de structures immergées telles que des pipelines dans l'industrie offshore illustre les possibilités d'intégration des résultats obtenus dans des missions opérationnelles. Le projet UNION regroupe sept organismes de recherche européens : (1)IFREMER, Subsea Robotics Laboratory (FR), (2) INRIA, SophiaAntipolis, ICARE Team (FR), (3) LIRMM-CNRS, Robotics Laboratory (FR), (4) UPC, Polytechnical University Barcelona (S), (5)LBM, Technical University Muenchen (D), (6)HWU, Heriot Watt University (UK), (7) Oxford University (UK).

Mots-clé : UNION, Projet européen ESPRIT, robotique sous-marine, commande, perception, navigation, programmation de missions robotiques, coordination bras/base

Contents

1   Introduction

The current state-of-the-art in underwater exploration is dominated by the use of Remotely Operated Vehicles (ROVs). These vehicles are typically controlled by a human user through a teleoperation interface. This form of operation is extremely flexible and powerful, but it is also very expensive, very tedious for the human operator, and very slow. The main problems are related to the coordination of the complex subsystems (the vehicle, its tether and its manipulation capabilities) under external disturbances. Also, the interpretation of complex disparate sensing devices must be enhanced.

1.1   General Objectives

Exploitation of *redundancy at both the acting and sensing levels* are the key issues investigated in the UNION project in order to propose solutions to these considerations. Also, adequate *programming environments* are designed to easily integrate the control and sensing results within complex operational missions.

To study *redundancy at the actuating and motion control level* means to consider as a unique controllable system the underwater mobile platform and its intervention effectors to execute a specific task in a robust and reliable way. Under these conditions and adopting the automatic control point of view, every task could be performed by selecting the degrees of freedom to be used in function of its peculiarities. As an experimental example, we consider the case of *a sub-sea intervention task for free floating vehicle (un-clamped) under disturbances* (waves, marine currents, or interaction with the close environment).

At *the sensing level*, integration and fusion processes of information provided by several exteroceptive and proprioceptive sensors are investigated. Such devices are: attitude, velocity, depth and heading sensors, sonar and video, telemeters including for example rigid manipulators with contact sensors. The objectives are twofold: first they allow world modeling and second optimal states of the system are estimated. The general preoccupations to exploit *redundancy in the sensor framework*, lead to define, like at the control level, the system with a certain number of degrees of freedom. They are selected according to the vehicle sensing capabilities and their choice depends on the specificity of the task. The sensing study is illustrated in the various phases of the mission example mentionned in the sequel.

Sensing and control aspects are not isolated and must be efficiently merged into theoretically well founded schemes. Therefore, sensor based control is of prime interest in the project to provide *reactive behaviour* and thus to *increase the level of autonomy of the whole system.*

1.2   Project organization: building-blocks and integration mission

All the aspects of the UNION project are illustrated by *building blocks*, each relevant to a particular scientific issue. Then, we have chosen to integrate these building-blocks, in a realistic mission profile. It involves tasks in a structured environment [29] that require the integration of teleoperation aspects together with full autonomous control within the same framework. The simple, but general, structure of generic missions is comprised of

three phases, each phase requiring both sensing and control developments. In UNION, the developments mainly focused on the two last phases.

1. *Search and Navigate to worksite*: Robot moves to the area where the objective of the mission is performed. This phase generally covers the period of robot operation from release at the launch site to arrival at the work area. Assuming that the site of operations is not well known, the robot will need to search a general area for exact site where the task is to be completed.
   As far as sensing aspects are concerned, this phase involves sensor modeling, dead reckoning, and navigation studies. Control main issues are related to modeling and specification and robust control of vehicle under disturbances and precise trajectory following. Both aspects are introduced in the first section of this paper.
2. *Dynamic stabilization on the worksite with sensors:* Upon finding and reaching the site, it is necessary to stabilize the vehicle in front of its given working area before the desired task can be effectively performed .
   To do that, new sensing technology and new sensing processing and fusion must be investigated. The outputs of these new sensing devices will be integrated into new control schemes for vehicle dynamic stabilization and precise trajectory following. The second section of this paper addresses both of these issues.
3. *Operation with free floating vehicle and/or manipulation tasks*: Once the vehicle is dynamically stabilized in front of the worksite, tasks, such as precise manipulations or pipe following, are performed by the robot. After completing the task, the robot is free to begin another task or to return to the home position in completing the mission.
   Typically, these tasks require robotics end-effector trajectory following, sensor-based control, hybrid position force control of manipulators and coordination between the manipulator and the free floating vehicle. These aspects are described in the third section of this paper.

Basic mechanisms for managing and programming the required actions are illustrated section 5. All the addressed theoretical themes are then merged in the canonical mission, described and programmed section 6. Finally, guidelines for the future are drawn in conclusion.

2 Search and navigate to worksite

In this part, the main research issues are associated to optimal dead reckoning and location update using natural or artificial landmarks. Precise trajectories are then computed and used in robust controllers to reach the worksite area. This investigates solutions to the principal difficulties limiting the actual performances of commercial systems, which are associated to non linear perturbations, sensors drifts and poor visibility.

2.1 Sensing

Location, path planning, maneuvering, obstacle/target positioning or sensor motion compensation can be achieved thanks to accurate position, velocity and attitude information.
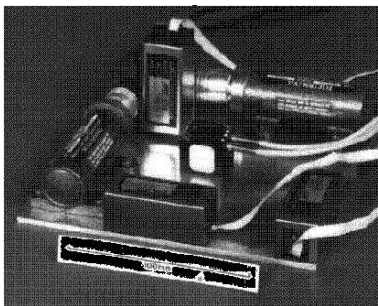
Figure 1: Low cost INS system

Accuracy needs strongly depend of the type of navigation (short, medium or long range), and of the mission phase. Inertial sensing (INS) and dead reckoning provide one component of localization as they supply a local, fast estimate of vehicle movement away from some fixed point. However errors accumulate, and regular updating of position with respect to the fixed point is required to supplement INS to maintain reliability. This requires the use of a second, independent measurement system, which can locate with respect to an external object. Most operational systems request in general active transponders to be placed on the sea bed, and generally yield accuracy of up to a few meters, depending on their depth and baseline.

2.1.1 Estimation of the vehicle attitude

The motivation of this work has been to develop an inertial system able to estimate accurate orientation of a vehicle (pitch and roll) by using the fusion of redundant data provided by two kinds of low-cost inertial sensors (Figure 1). The first method [35] consists in corre-lating the pitch and roll angles computed by using the gravity components obtained from two accelerometers. It consumes estimations resulting from the integration of the angular velocities measured by three orthogonal gyrometers. A fusion by extended Kalman filtering is performed to benefit from both measurements.
However, the Kalman filter performances are strongly dependent on the adequacy of the a priori error models of the sensors. To deal with this problem, we developed and tested a new filtering approach which uses fuzzy intervals to represent in a same framework both the accuracy and the reliability of a measurement. Then, fuzzy inference theory is used to include semantical knowledge about the sensors behaviour [34].

2.1.2 Terrain based and target tracking based navigation

An objective of UNION is to provide effective terrain based navigation methods capable of supporting automatic stand-off and/or trajectory following. Because of narrow beam sonars limitations (price,data interpretation difficulties) we propose to employ a wide beam sonar device, operating at a lower frequency.
The success of interpretation of single wide angle sonar [19, 31], is based on the detailed examination of the physics of the projection and reflection of ultrasound. In the project, for better performance, we use a differential sonar device (Figure 2a.) rather than a single wide
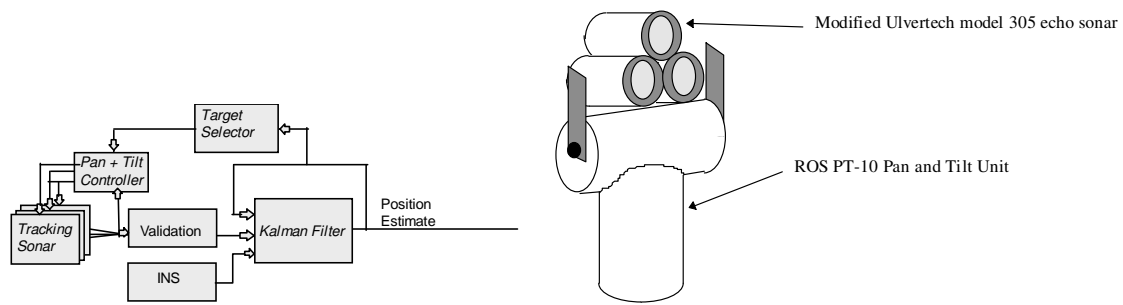
Figure 2: a. System architecture – b. Differential time of flight sonar

angle sonar to track a feature given suitable processing and scanning action. Tracking is implemented using a Kalman filter. To handle the correspondence problem between images the feature needs to be described at a higher level than just a raw range point; otherwise ambiguity is a major difficulty. Therefore it is vital to extract as much information as possible about a target in a single image so reliable correspondence can be established rapidly. Multi-hypothesis filtering can be used to deal with ambiguous sensor data but is computationally very expensive.

The sonar comprises five major components (Figure 2b.): the tracking sonar transducers, the pan and tilt head controller, a target selector, validation unit for the targets, and a Kalman filter for estimating vehicle localization (which also has as an input the data form the INS). To obtain real-time bearing information for 3D tracking, we propose to use differential time-of-flight information from three (or more) transducers observing the same target. Considerations of visibility and interference mean that the best results are obtained when all three receivers are quite closely spaced and measure the time-of-flight of a sound pulse from a single closely spaced transmitter [20]. The sonar sensors consist of a trio of synchronized sonars (three modified Ulvertech model 305 depth sounders) mounted co-axially on a single pan and tilt unit. To avoid interference effects due to cycle firing overlap and target motion effects, the depth-sounders were modified to operate in a single-transmitter multiple receivers mode.

For the purposes of the sonar model, the geometry of environmental features is assumed to approximate one of a small number of geometric forms: planes, spherical patches, cylindrical patches, edges, corners, and points (cf [3, 18] for experimental results and comparison with more sophisticated classification [5]).

Initial trials with sonar/target aspect fixed for long periods established an effective beam-width, of around 15 degrees. The measured range distribution was approximately normal with a 3.5mm (half-wavelength!) sigma bound for targets at a range of two meters. Unfortunately, these excellent results could not be replicated trials with targets being scanned to assess tracking performance produced much lower quality data.

The presence of a strong bias towards false long readings at the edge of the beam, that means that the effective beam-width across which useful range/bearing data can be obtained is actually rather less than 8 degrees (Figure 3a.). The bias in range observed for off-axis targets does, however, appear to be reasonably consistent between all three sonars. Figure 3b. shows differential time-of-flight from a typical scan across a target.
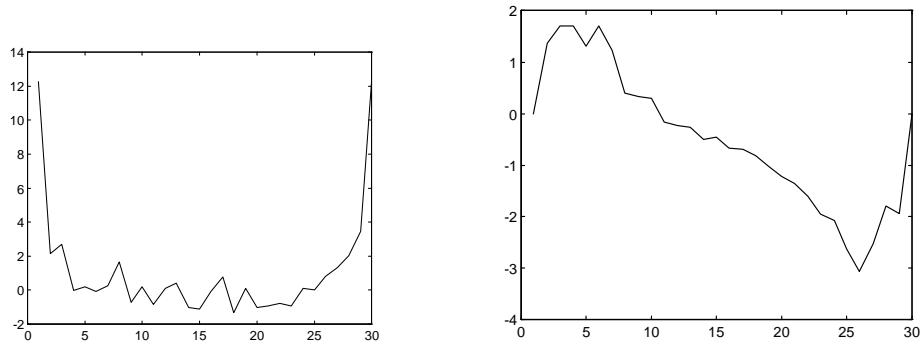
Figure 3: a. Error in range across horizontal scan of vertical cylinder – b. Differential time-of-flight across horizontal scan of a vertical cylinder averaging 6 returns at each point (x axis units: 0.5 deg, y axis in cm)

Preliminary tank trials have confirmed that the differential time-of-flight data can be used for tracking, in an experiment to track a cylinder moved slowly across the tank at a distance of a few meters.

The classification data-fusion task to be performed is thus one of simultaneous mapping and localization rather than just localization. The available sensor data has to be combined to estimate the locations of the sonar targets as well as the vehicles location relative to these targets. In practice, serious combinatorial problems arise. The difficulty is that the various positions estimates (target and vehicles) are cross-correlated. The result is that a full Kalman filter update to estimate target/vehicle positions cannot be computed in better than $O(n)$ time, where n is the number of sonar targets.

In UNION, to overcome these shortcomings, we use a new approach based on a partitioning of the estimation task. For any plausible sensor management strategy, the set of targets observed at any given time will be stable and geographically clustered. Close targets will be favored over distant targets, with sensors being occasionally re-assigned as targets are lost from view or better targets come into range. Given the relatively small number of sensors available, the number of targets in each cluster is likely to be quite small. Thus, by maintaining independent filters for vehicle state and features for all clusters, but updating only a few (the current cluster and selected neighbors containing observed features) it might, in principle, be possible to implement an adequate sub-optimal but scalable navigation filter.

2.2   Control

Once localization is efficiently performed, a trajectory can be generated and consumed at the control level. One of the main issues is then to design robust control schemes with regards to external disturbances and estimation errors. In order to evaluate these controllers, modeling and simulation tools must be used. In the mean time, the feasibility of the implementation on targeted real-time architectures, must also be tested. Therefore, the next paragraph highlights the modeling and simulation aspects at the basis of the design of the robust controllers described sections 3.2 and 4.

The design of a robotics system is both a difficult and a costly task. This difficulty arises from the complexity of such systems which usually involve various mechanical systems, sensors and computers which communicate between each other. The behaviour of mechanical systems is described by integrating, with respect to time, the differential equations which they satisfy. Consequently, the evolution of such systems is continuous in time. On the other hand, sensors and computers belong to the digital world. Their behaviour is described by discrete events. Because of the cooperation of the continuous and the discrete worlds, the complexity of robotics systems is increased. Finally, robotics systems demand expensive, high technology components. Errors in a design can result in physical damages or a complete loss of the system especially in the case of underwater robotics. For these reasons, realistic simulation is an essential step in the design of robotics systems. The SIMPARC [4] (SImulator for MultiProcessors Advanced Robot Controllers) general simulation software is developed and used in the project. It is designed to *handle both the continuous and the discrete aspects within a single simulation system*. The commercially available MATLAB simulation tool is also used for dynamic simulation of the studied systems.

In the context of UNION, we have customized SIMPARC in order to account the requirement of the project: underwater platform and manipulator arm, vision and ultrasonic sensors, 3D scene modeling can now be modeled. We simulated sensor-based tasks using vision or range sensors on board of VORTEX vehicle (figure 7a.) in a realistic way (cf section 4). More precisely, we have developed:

- a geometric model of 3D underwater scenes;
- various models of exteroceptive sensors based on vision and acoustic principles;
- kinematic and dynamic models of the vehicle (figure 4a.) and the on board arm (figure 7b.);
- visualization and analysis tools for exploiting results (figure 4b.).

All these improvements have been used in the simulation of visual pipe following tasks described section 4.

3   Dynamic stabilization on the worksite with sensors

Close to the worksite the principal problems arising are mainly related to stabilization, station keeping and once again precise trajectory following using proprioceptive and exteroceptive sensors. In this part, the stress is put on the sensing requirements and the developments of original control schemes built to solve these problems.

3.1   Sensing

One of the main originalities of this project is to propose coordination and integration of sensory information provided by imaging sensors (sonar/video), range finders (laser/sounders) and attitude, velocity and acceleration devices. Here, the biggest difficulties is the estimation of zero-velocity states.