ADVANCED CONTROL FOR AUTONOMOUS UNDERWATER VEHICLES

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ABSTRACT

Ifremer operates manned and unmanned submarines for scientific exploration since many years. The need for more classical survey AUV (Autonomous Underwater Vehicles) has arisen within Ifremer's scientific programs these past years. The maturity of the AUV technology has permitted to set-up and launch an operational program for a fleet of coastal survey AUVs within Ifremer. R&D activities performed by Ifremer since many years on advanced control, diagnosis and embedded software architecture, find in this new generation of operational Underwater Vehicles a real field of application.

This paper describes current development on on-board supervision software architecture aiming at increasing the security of an AUV and its environment, while improving its performance.

KEYWORDS: AUV, Intelligent Control, Embedded Architecture.

1. INTRODUCTION

Ifremer has been engaged for many years in underwater technologies and in the operational use of underwater systems within the French oceanographic fleet. Development of the deep sea ROV *victor 6000*, and a complete upgrade of the well-known manned submersible *nautile*, are some of the major activities undertaken recently by the Underwater Systems Department within Ifremer.

In parallel to these operational vehicles, and in order to be ready with a new generation of underwater systems, R&D activities have been pursued in a wide spectrum of areas, and in particular within AUV technologies domain.

In the context of deep water technology development, numerous projects mainly targeted for offshore applications have been conducted recently by Ifremer with European industrial and research partners. This effort started in 1998 with the development of the supervised AUV *sirene* designed for accurate launch and deployment of a benthic station [1]. The technology developed in this project has then been applied to the *swimmer* project [2] aiming at developing an hybrid AUV, designed as a shuttle for carrying a classical ROV and deploying it once docked on a pre-installed bottom-station.

The successful development of these projects conducted in going further within the domain of autonomous intervention in the frame of the *alive* project aiming at the development of an Intervention-AUV (I-AUV) capable of advanced control for autonomous docking using vision- and sonar-based control. During this project, a significant breakthrough in both optical dynamic positioning in a local environment and precise autonomous docking was made [3][4].

Beyond these technological advances, the need for a more classical survey AUV has arisen within Ifremer's scientific programs. This has led to the set-up and launch of an operational program for a fleet of coastal survey AUVs.

The industrial capability to provide survey vehicles was broad enough in 2002 to justify the launch of an international tender for a generic vehicle, which would allows Ifremer to retain control over the continuing development of other specific technologies related to navigation and positioning, communication, data exploitation and modular payload development.

2. AUV PROGRAM AT IFREMER

Requirements and basic specification

Scientific needs have arisen for multi-sensor underwater surveys. This is particularly true in the fields of physical oceanography, marine geology and fish stock evaluation in the continental shelf and margin regions where socio-economical demands are fuelling the need for more detailed surveys. Those needs have led Ifremer in 2002 to launch an AUV program with the aim of using autonomous vehicles for operational scientific survey by 2005.

The analysis of scientific requirements, collected from several French and European oceanographic institutes, has led to the specification of a 600 to 800kg, 3000m depth-rated, modular vehicle with more than 100km range capabilities, and around 200kg payload capacity. For coastal applications this vehicle must be operated by a limited crew team from small (<30m) non-specialised or opportunity vessels.

The final objective of this program is the systematic set-up of an operational fleet of AUVs for re-active environmental survey. This fleet will react to unforeseen events such as meteorological phenomena, seismic activity, and accidental pollution.

The use of such an AUV in coastal areas dictates rules for usage, and an evaluation of operational risks. This has led us to select a basic operational scenario, in which the vehicle will surface only if an escort vessel is able to manage the security on the sea-surface. In other cases the vehicle will not be permitted to surface without acoustic contact with the escort vessel and will remain underwater, or ultimately lie on the bottom and wait for the escort vessel to command it to surface. For this reason, sophisticated acoustic communication and relocation functions have been included in the functional needs.

The vehicle selected for the first system is derived from the Explorer-class AUV, designed and built to Ifremer specifications by ISE Research Ltd [5], in association with the French company Cybernetix. It has been named *aster*^{x} by Ifremer .

Technical cruises and the first scientific operation of *aster*^{x} have been carried out in 2004 and since then *aster*^{x} is intensively used as a scientific demonstrator as well as a technological platform for on-going development.

Some subsystems of *aster*^{x}, such as communication and navigation, payloads, and data exploitation software have been provided and integrated by Ifremer in order to facilitate the ongoing technical development of these systems by French companies.

Typical payloads are already in design and test phase :
- Current profiling and physical-chemical parameter measurement
- Sonar imaging for fish-stock evaluation
- Bathymetric sonar, sub-bottom sounder and side-scan sea-bed investigation

General Design of *aster*^{x}

aster^x is approximately 4.5 metres in length with a diameter of 0.69 metres (27”). Depending on the payload its weight is between 580 and 800 kg in air, with a diving depth of 3000 metres. Its cruising speed is between 0.5 to 2.5 m/s.

Figure 1. the *aster*^{x} AUV © Ifremer

Control subsystem, networking and data logging

The VCC ("Vehicle Control Computer") system is an industrial rack-mounted Compact PCI computer with built-in expansion capability. The vehicle I/O uses a combination of distributed and local devices. There are digital and analogue input/output, including an Ethernet network switch and serial link.

A dedicated board provides a Network Time Protocol (NTP) service to other network nodes, and allows subsystem synchronisation by generating TTL sequences. Time synchronisation is obtained from the PPS-GPS, when satellite lock is available. All data logging performed by the VCC reflects this GPS referenced time in UTC. Two Ethernet 100Mb port connections to a network switch are provided to the payloads for data communication.

A 10GB hard-drive stores software executables, mission plans, and vehicle data log files. All critical vehicle mission information is logged to the hard-drive during operation, at a configurable desired rate. The lists of parameters to be logged are modified on the SCC ("Surface Control Computer") and archived with the mission plan files for future reference. At the end of a mission, data log files are uploaded to the SCC and also stored with the mission plan files.

Surface control and display systems

For flexibility the surface consoles are portable. They contain the following equipment:

- The SCC ("Surface Control Computer").
- Positioning system
- DataLinc 2.4 GHz Ethernet radio.

The SCC has interfaces with the following equipment:

- Umbilical Telemetry
- Acoustic Telemetry
- Radio Telemetry
- Surface Positioning System

The operator interface displays vehicle information in both graphical and text forms as appropriate.

Mission programming

Mission plans are defined by ASCII text files containing mission task verbs : built-in keywords and comments. The built-in keywords are "entry label" and "goto" which together can be used for "looping" and "jumping" within a mission. The task verbs fall into two categories: geographic and other. Geographic tasks are closely tied to a geographical position (latitude & longitude). Other types of tasks are not closely bound to position and include for example the ability to turn equipment on or off for specific parts of the mission. Each geographic task has a configurable vertical mode (depth or altitude), a vertical setpoint, a speed mode and a speed setpoint. Using a series of task verbs with differing depth or altitude setpoint, it is possible to plan a mission with virtually any 3D trajectory. The current list of geographic task verbs includes “target”, “line_follow” and “circle”, but can easily be expanded by editing a grammar definition file and including the necessary configuration to make the AUV carry out the new task.

The MIMOSA software (“MIssion Management and Operation for Subsea Autonomous vehicle”), currently under development and test at Ifremer, will be an optimised tool proposed to the scientific users of the AUV for mission description and programming.

Mission plan files are generated and simulated at the surface console (for final validation), then downloaded to the vehicle using any suitable data link, including the Ethernet radio modems.

3. ON-BOARD SOFTWARE ARCHITECTURE

Description

The controller of the vehicle is based on ISE’s ACE (“Automated Control Engine”) system and on the already proven architecture used on the “Theseus” vehicle by ISE [6]. The primary capabilities of vehicle control software are mission execution, guidance, control, fault detection and energy management. In order to provide these capabilities the system is broken down into subsystems. Each subsystem is assigned a specific task, which is self-contained, testable and less complex than the system as a whole. The subsystems further break down tasks into ACE software components. This approach maximises flexibility of the control system. When change is necessary, often only one ACE component is affected in the subsystem.

The VCC (“Vehicle Control Computer”) design is hierarchical with the mission plan manager at the top and the low level control loops which control the planes and the thruster at the bottom. The interconnection between subsystems is implemented by event propagation. External access to events, to inject or read values, is provided by various existing message-passing interfaces. The main subsystems are:

- Mode Manager: top level system for controlling the overall state of the vehicle, enabling subsystems appropriately and includes mission execution control as well as fault management and responses.
- Guidance: receives trajectory information and waypoint positions from the mission plan manager, as well as vehicle position information from the positioning sub-system.
- Positioning: interfaces with the vehicle navigation sensors and outputs the vehicle position in latitude and longitude.
- Energy Management: monitors past and predicted future energy usage and generates fault conditions to abort or modify the mission when problems occur.
- Control: closed-loop planes position control and closed-loop speed control.
- Telemetry: Data is transferred between the SCC and VCC via the Telemetry module. The telemetry system has been specifically developed to use an acoustic modem, as well as packet radio and Ethernet links.
- Logging: Any data can be logged on the vehicle computer at a configurable desired rate.

Emergency sub-system summary

For security aspects, the vehicle is fitted with several devices such as a weight recovery, a self- powered Novatech Model ST-400AR strobe light, a self-powered ORE 4336B acoustic pinger/transponder and a self-powered Novatech RF-700AR. radio beacon.

The fault manager system detects vehicle faults and takes pre-defined fault action. These actions can be programmed in a look-up table and can be different for various mission phases. Examples of fault responses for the vehicle include “STOP and surface”, “STOP and park on the bottom”, “Change mission step”, or “Ignore the fault and continue”.

4. DESIGN OF ON-BOARD SUPERVISION CONTROLLER

R&D activities background

Ifremer has been involved in ADVOCATE and ADVOCATE II European projects conducted from 1998 to 2005 which aimed to design and develop modular embedded software architecture for intelligent and advanced control of autonomous systems like AUV [7].

One of the main objective of these projects was to specify and design a modular software architecture able to be plugged onto an existing control architecture. Main efforts have been put on the specifications of the interface between existing and new software architecture. This study resulted in the definition of protocols of data exchange, nature of data to be exchanged, and level of interaction of the supervision and diagnosis software architecture over the existing piloting one.

The goal of this new software architecture is to detect and diagnose malfunctioning in the monitored vehicle in terms of subsystems (sensors, actuators, payload, energy source,...) or behaviour (mission execution, high-level control, diagnosis and decision). This architecture and its intelligent components has been successfully demonstrated at the end of the ADVOCATE II project on the Atlas Elektronik GmbH AUV MiniC in April 2005 [8].

Description of PSE

The outcomes of this project have been exploited by Ifremer for improving the on-board control architecture of the *aster*^{x} AUV by designing the PSE software module (PSE is the French acronym for "Embedded Supervised Piloting").

PSE is designed as an on-board supervision module able to monitor the functioning of the AUV and its subsystems (sensors, actuators, energy source), and to monitor and supervise the mission plan execution with the objective to verify the nominal execution of the programmed mission plan and modify locally or globally the mission plan when the actual AUV behaviour and functioning is different from the nominal one.

The abnormal situations can be numerous. For instance:

- Malfunctioning or failure of a subsystem (sensor, actuator,..)
- AUV behaviour is not the expected one (unforeseen evolution of the environment characteristics like underwater current for instance) which can lead to undesired situations such as increasing the energy consumption, missing a "rendezvous" in the mission (geographical, temporal,..)
- Detection of an obstacle

The specification of PSE has been made in such a way that its activation/deactivation does not impact the nominal functioning of the vehicle architecture. In any case, the "last word" is always given to the fault management system of the AUV in charge of critical faults management. The PSE objective is to limit or avoid undesired mission abortion when the encountered situation is not a real critical one, and when a modification of the mission plan or the vehicle configuration can optimise the use of the AUV evaluated through the scientific data collection.

Internal design of PSE

The PSE module is built around an expert system. All data generated by the AUV or useful for its monitoring are handled by PSE: sensors and actuators data, payload status, energy monitoring system, mission plan execution,...all types of data are supported by PSE (numerical and non numerical data).

A rules database, subdivided into "Diagnosis rules" and "Decision rules" with different activation and analysis methods managed by a dedicated and powerful inference engine are defined. "Diagnosis rules" perform the diagnosis on the situation and produce input data for the "Decision rules" in charge of determining the best recovery actions to overcome the diagnosed abnormal situation. The set of recovery actions contains:

- Modification of one or several parameters of the nominal mission : for instance, increase the vehicle speed in order to be on-time for an imperative “rendezvous”, change the vehicle altitude for increasing the quality of the data collected by the payload sensors,...
- Suspension of the nominal mission plan for execution of a local trajectory (obstacle avoidance for instance) and then resume the initial mission
- Short-cut the nominal mission plan for instance when energy consumption is higher than planned
- Change the nominal mission plan for a new one (built by PSE or taken from the PSE knowledge database)

Once the recovery actions is determined thanks to the activation of the Decision rules, PSE initiates a dedicated dialogue with the vehicle controller in order to apply its decision.

Configuration of PSE

The configuration of PSE consists in “programming” the intelligence of PSE: the different set of rules for diagnosis and decision, as well as the integration of additional intelligent processes and functions integrated within PSE as external functions. For instance, it is planned to integrate automatic mission planning algorithms, obstacle avoidance algorithms or advanced diagnosis modules [9].

The NEMO software suite

PSE is part of a complete software suite called NEMO which consists, in addition to the on-board PSE module, in a set of different tools dedicated to development, configuration, analysis, and monitoring:

- Configuration module. Allows to configure PSE: management of the diagnosis and decision rules, configuration files, selection of the monitored data, selection of the logged data,... This stage results in the production of “PSE configuration files” to be downloaded into the PSE module for execution on the AUV
- Analyser module. Allows to replay and analyse logged data. These data are not the AUV data already logged in the VCC, but the internal data produced and manipulated by PSE. For instance, the rules fired by the inference engine and the diagnosis and decisions performed during the mission execution.
- Monitoring module. Used for the supervision and control of the internal/external functioning of PSE when a communication link exists with the AUV or when running on the simulation platform. A dedicated man-machine interface is then used for displaying the evolution of the internal state of PSE (diagnosis and decision rules, data,...)

Current development and objectives

A simulation platform is currently under development and will be progressively used for testing and validating the PSE module and the associated NEMO suite tools. This simulation platform consists in the duplication of the complete computers configuration of the real AUV: SCC and VCC, communication link.

Within the platform, the AUV behaviour is simulated thanks to a dynamic model of the real vehicle. The vehicle state obtained from this model are then injected in a sensor simulation software providing a set of message data having the same format than the real sensing devices. This allows to use in the platform the same VCC software, with in particular the same protocol and communication links, than on the real vehicle.

The development of the complete NEMO software suite is currently on-going, and will be completed by the end of 2006. Progressive integration and test of its software components will be performed on a simulation platform of the *aster*^{x} AUV, allowing to test critical situation without any risk for the real vehicle. First implementation and tests of the PSE module on the real AUV are planned for the end of 2006.

5. CONCLUSION

The PSE supervision module, part of the NEMO software suite, aims to supervise and monitor the *aster*^{x} AUV during the execution of mission. The PSE module will be able to detect any malfunctioning in the AUV subsystems, or any abnormal situations during the execution of the programmed mission plan. The level of interaction of the PSE module with the vehicle control architecture relies on real-time adaptation of mission parameters, or modification of the mission plan itself.

Preliminary results concerning the first use of the PSE module are expected to be obtained on the simulation platform of the *aster*^{x} vehicle by the end of 2006. Progressive integration and test of PSE on the real AUV itself will be conducted later on.

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