DESIGN OF AN UNDERWATER INSPECTION SYSTEM USING A REMOTELY OPERATED VEHICLE

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Abstract: This paper describes the specification and design of a prototype of a low cost open system for the inspection of underwater structures based on a remotely operated underwater vehicle under the project IES, a 3 year long effort funded by the Portuguese R&D program Praxis XXI.
Unlike commercial approaches, a modular open system characterised by the incorporation of an on-board computer allowing for advanced control capabilities is envisaged. The control console is based on a standard PC and the tether is used only for power delivery and to establish a simple communication channel. In this project, we use advanced hybrid control techniques for sophisticated semi-autonomous operation management and control. The control architecture reuses part of the one designed for the underwater vehicle Isurus operated by the Laboratory of Underwater Systems and Technologies of Porto University. The implementation is designed in order to allow for multiple sensor configurations specified as add-ins. This leads to a dynamic, scalable and flexible system that can be easily configured according to the user specifications.

Keywords: Remotely Underwater Operated Vehicle (ROV), Underwater Inspection, Control System for ROV, Navigation System, Hardware for ROV

Introduction

The use of Remotely Operated Vehicles in underwater inspection has been a long-standing practice in industry and in the academic community [1], [6], [9], and, with the growing interest in marine operations, their range of applications has been diversifying.
One of the main advantages of the traditional ROV's is their reliability, which is due mainly to their simple design with small integration of control electronics and onboard wiring. However, this simplicity also implies serious limitations in terms of maximum task complexity and in the tether dimension (which increases operational difficulties). Besides the reliability issue, the other main reason for keeping the vehicle simple is the cost. So far, it has been either too expensive or too difficult to include enough on-board processing power to provide substantial new and useful functionalities.

The wider availability of more powerful, low cost and small-sized (and, thus low consumption) computers and the associated impact in the AUV technologies development and research made it possible to incorporate high processing power and sensing capabilities in a conventional ROV. In this way, a wider range of applications can be addressed at a much lower cost than previously possible.
In this paper, we address the development of a particular underwater inspection system. Although ROV-based, the proposed system involves substantial know-how acquired in AUV research in a essential way. In particular, the system's design and development and operational experience gained with *Isurus*, a REMUS class AUV at the Underwater Systems and Technology Laboratory of Porto University will play an important role.
The addressed application scenario is those of the inspection of submerged portuary infrastructures, and was strongly motivated by actual concrete needs of APDL, the Port Authority of Douro and Leixões. In this way, the EUREKA project IES was proposed by an international

consortium whose R&D activities are essentially supported on the underwater technology and robotics experience of the Underwater Systems and Technology Laboratory [7],[8].
The goal of the project is to design and develop an open highly operational, easy-to-operate inspection system tailored to the specific requirements of APDL. Furthermore, low cost, advanced capabilities, low maintenance costs and manufacturer-independence are additional requirements which will be crucial in the future system's commercialisation.
Our approach is to start with a conventional small size inspection-class ROV and extend its capabilities by incorporating on-board processing and sensing capabilities. This makes it possible to use much more elaborated control schemes than the usually commercially available ROV's. Furthermore, higher vehicle manoeuvrability will result from the reduction of the number of cables in the umbilical chord.
This higher integration is oriented towards two main goals: allow the system's operation by a person with minimal training and keep the design as simple and open as possible. In particular, the system will be designed so that new sensors and payloads can be easily incorporated, thus increasing its versatility.
Additionally, special attention is being paid to the development of the operation console and the surface equipment. The operation console has not only to provide a good interface to the system, but also, a means of distributing information (such as images) to various agents, possibly after some specific automatic data processing and analysis. With today's networking technologies, it is possible not only to disseminate the retrieved information to experts located away from the inspection site, but also to enable them to, at least partially, control the inspection process.

Underwater systems and techonology laboratory

The Underwater Systems and Technology Laboratory (LSTS) of Faculdade de Engenharia da Universidade do Porto (FEUP) was established in 1996 and counts with researchers from the Decision and Control Engineering Group of FEUP and the Institute for Systems and Robotics (ISR).
The mission of LSTS is to explore interactions and synergies between the most recently developments on the underwater technologies and the Decision and Control Engineering to allow the design and implementation of new paradigms for ocean and ambient inspection of Portuguese cost waters.
From the projects actually in curse we detach the 2 following:

- PISCIS - Underwater Observation System based on Autonomous Underwater Vehicles (AUV). Many missions were developed to attain those underwater observations. Douro River and Minho River were observed using this technology. The main objective of this project is the development and demonstration of viability of an oceanographic observatory based on coordinated operation of multiple AUV. A new AUV has been developed to satisfy this objective.
- IES - Inspection of Underwater Structures [10]. The main objective of this project is developing a prototype of a Remotely Operated Vehicle (ROV) for multi-modal inspection of underwater structures. This project is described in detail in this paper.

System Requirements

Inspection problem addressed

The Port Authority of Douro and Leixões is mainly concerned with the inspection of structures in the commercial part of the port. There, one of the main problems of interest is the identification of the state of corrosion and detection of eventual structural problems in the vertical underwater walls of the dock. Corrosion problems arise mainly in the union of the steel tiles covering the mentioned walls. The typical site in this scenario has average depth of 10 m and an extension of 300 m.
Periodically, divers collect video images and sample materials in order to allow the assessment of the state of the wall. When the diver detects some kind of irregularity, it takes images for the inspection specialist engineer to analyse. The most frequent problem detected is corrosion in the metal tiles which can be characterised by depressions of ca 1 to 2 cm deep which extend for a few meters long.
Upon detecting the problem, the site must be marked and the position of the diver known so that the necessary repair work can be performed later. Therefore, positioning precision plays an essential role.
Near the above mentioned walls (deep inside the harbour), waves are almost negligible and the main underwater perturbations are caused by passing ships. The only source of water current is caused by the small river Leça and thus also negligible.
In spite of the very calm conditions, visibility is often very bad: typically, the depth of the vision field is ca 2 m. This lack of visibility is caused by the pollutants drained to Leça river by industries located upstream. For obvious reasons, visibility is maximum every early Monday morning. Another important obstacle to the inspection activity is marine growth, usually seaweeds, witch very often cover the walls. This growth occults some of the cracks and corrosion beneath, so that often the divers have to use tactile means to detect them.
Another inspection problem with similar characteristics is the detection of the corrosion of metallic poles in the piers. The environmental conditions are the same, but, in this

case, the inspection is performed beneath the pier since only the top 4 m are concrete blocks supported by pillars. On the back, there are curtains of metal poles that have to be inspected.

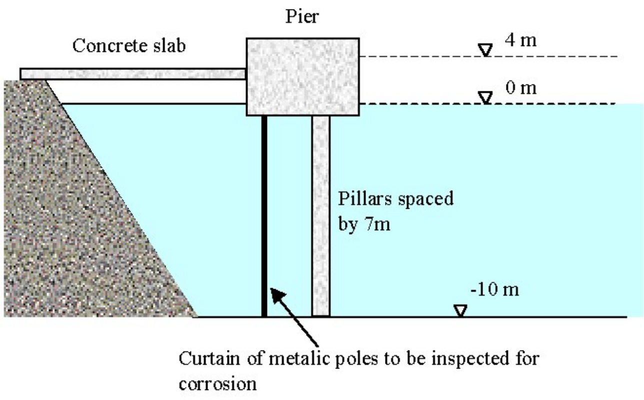

Fig. 1- An inspection scenario in the port of Leixões.

The inspection of this curtain is only performed when a problem is detected in the ground near the dock. This is a concrete stab supported between the ground and the dock.
Another type of problem of interest is the conservation of concrete pillars in the outer parts of the harbour. There, the environment is harsher with ondulation that can reach 1 m and currents that can reach 5 knots.
Other types of inspection problems are also needed such as verifying the state of the concrete tetrapods on the outside of the harbour. This is already at open sea and the conditions there are very harsh with strong currents and waves.
The port authority showed a special interest in a general-purpose inspection system that could be used by a technician with little training in ROV operation.
Additionally, an important class of applications to be envisaged by APDL in the future and to which the system should also be able to deal with is to inspect ship hulls both in the context of ship's maintenance programs and during loading and unloading operations. That would require a very fast operation, since the hull has to be inspected in a relatively short period of time.

Control requirements

The use of the vehicle by a person with limited ROV operation training, together with the classes of inspection operations to be performed impose the need of a diversified set of complex vehicle control modes.
In a traditional ROV, the operator either controls directly each thruster or has some kind of autopilot such as heading and depth autopilot. Here, we extend the control of the vehicle, by providing a higher level control layer allowing the execution of complex and application adjusted manoeuvres.

With respect to the vertical walls, one type of mission to be performed consists in the systematic survey of the wall.
One useful manoeuvre would be, moving in a vertical plane at a fixed distance from the wall. To achieve this, the vehicle controller would always have to regulate both the position in a plane parallel to the wall and the attitude to face it perpendicularly. This could be achieved with the help of a vision system pan&tilt unit, which could compensate unwanted relatively small disturbances in de attitude of the vehicle. The operator only issues movement commands in the vertical and horizontal directions.
A generalisation of this control mode is the ability to command the vehicle with 2D movements within a surface defined by the set of points at a fixed distance to the structure (this requires a much more accurate control of the vehicle, namely in what concerns pitch and roll). In this way, the image could be kept stable and the operator only moves the vehicle along the structure to examine it.

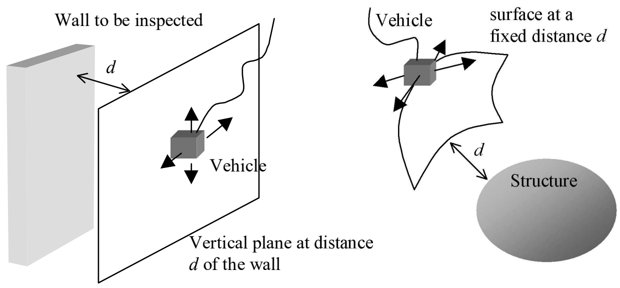

Fig. 2- Complex manoeuvres for inspection.

Another type of manoeuvre is hovering. Upon finding some point of interest, it should be possible to issue a hover command, which will cause the vehicle to maintain position and orientation. The control system should be capable of compensating the inspection wise significant disturbances. A slightly different objective consists in locking a video camera to some target. In this manoeuvre, the camera is kept pointing to some feature in the structure while the vehicle could be moving back and forth perpendicularly to the feature.
One important capability of the system is the possibility of specifying predefined positions in absolute or relative 3D Cartesian co-ordinates and of issuing GOTO commands. These will cause the vehicle to travel to the specified positions without operator intervention. This is of interest when, upon detecting some problem at some point in a structure, it would opportune for the vehicle to visit that spot in a later occasion, possibly when performing a different mission. This kind of manoeuvre has some strict requirements in terms of navigation since it needs some kind of absolute positioning system (being the most promising an acoustic one).
To inspect pillars and columns, a good manoeuvre is to move in circles at different depths with the operator controlling de depth and the position in the circle.
Furthermore, in cluttered environments and for safety reasons, it is desirable to have some kind of obstacle

detection and overriding or correction of the either active or pending tele-operation commands.
These high level control modes, coupled with complex mission objectives, such as performing automatic wall-sweeping (moving along a grid or a predefined trajectory) as the ones usually found in AUV's [7], [8] would allow improvement of the inspection capabilities of the vehicle.

System Description

Hardware

One of our objectives pursued in the project was keeping the size and weigh small, and yet allowing the embedding of onboard processing power, new navigation sensors and capability of adding new inspection sensors. The desired vehicle should be transportable in the back of a normal car and carriable by 2 to 3 persons. That imposes a limitation of overall size at about a parallelepiped of 1mx1mx.8m and maximum weight of 60 Kg.
Two options were considered in the design phase: either to develop an entirely new mechanical frame (with the pressure hulls and thrusters), or to start with a commercial ROV system and modify it according to our requirements. The latter was chosen due to significant advantages in cost and developing time.
The mechanical base structure of the vehicle consists in the modified industry standard inspection ROV Phantom XTL from Deep Ocean Engineering (shown in figure 3). This was chosen according to the constraints mentioned above and to the ease of adaptation.

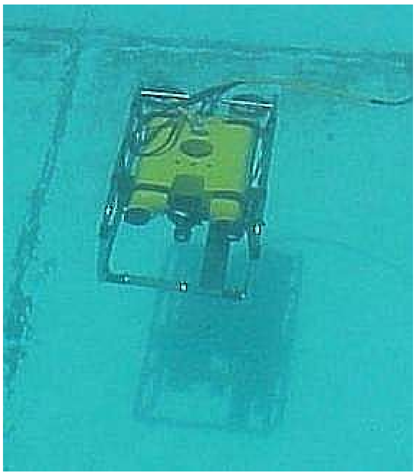

Fig. 3- Remotely operated vehicle used in IES

The original vehicle was enlarged and an extra pressure canister (50cm length and 17 cm diameter) was added to incorporate new onboard electronics (CPU, navigation sensors and others).

The standard thrusters were modified in order to have them fitted with optical encoders (required for advanced closed loop control of the vehicle).
The vehicle has 4 thrusters: two main forward, one vertical and one lateral. Thus, it does not has active control of pitch and roll. This was chosen by two reasons, keeping the vehicle cost low as well as its size and weight bounded due to operational reasons.
To accommodate the new canister, the crash frame was enlarged to about 60 cm x 60 cm x 110 cm. Also due to the additional of components, the vehicle flotation was increased.

Computational System

The computational system (shown in figure 4) to be incorporated onboard was chosen to be standard Pentium based PC, with PC104 form factor. The low cost, high performance and very small form factor is crucial in the system since it must be placed in the pressure cylinder with only 17 cm of diameter.
We have already gathered experience with this kind of systems with our REMUS class AUV Isurus. It proved to be reliable and powerful.
The size of the canister allows the PC104 stack to have at least 5 boards, so additional ones can be easily added as needed, such as: additional serial ports, I/O boards or other interfaces.

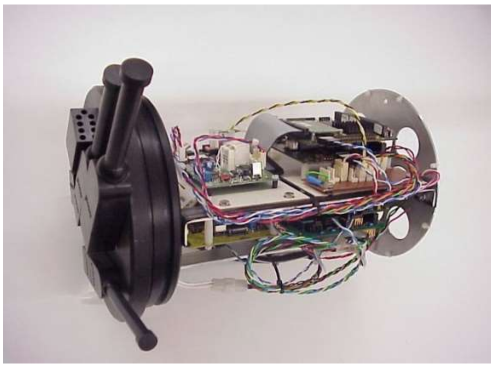

Fig. 4- The computational system placed in the pressure cylinder.

The onboard computer is responsible for the control of all the aspects of the vehicle as well as the management of communications with the surface.

Communications system

Due to the distributed nature of the vehicle (3 pressure hulls and several flooded components) the communication

between the various subsystems becomes an important issue.
Many of the sensors have traditional serial interfaces (such as RS-232), others provide direct analogic readings and need proper signal conditioning.
One important objective to be met, is to keep the wiring as simple as possible, and, yet, allowing modularity and good communication bandwidth. Since the onboard computer must communicate with numerous sensors and actuators, the use of dedicated lines to each device increases the number of required connectors and underwater cables. If we note that the area available for underwater connectors is at a premium (the endcaps of the pressure canisters), it becomes obvious that the traditional star configuration is not the most adequate.
That leads us to a bus configuration. This was based in our previous experience with the *Isurus* (with the actuators in a RS–485 serial bus) [2], and with the land-based system Po-Robot [4] where a serial sensor bus is used to interface with the different types of sensors. For the present system wee chose CAN. This type of network was originally developed in the auto industry and was already implemented in underwater systems [5]. It allows to overcome some of the problems addressed in the context of the ROV design phase.
One of CAN's [3] main advantages is the large base of applications and industrial acceptance which leads to low cost and wide variety of commercial of-the-shelf components. Furthermore, it allows multi-master multi-slave communications and high bandwidth (with attainable transfer rates of 1 Mbit/s), and low current consumption devices.
The CAN protocol has built-in error detection and good noise immunity due to it's differential communication scheme ensuring reliability in the communications. CAN guarantees bus access of a high priority message within 150 μs (with 1 Mbit/s baud rate) after first attempt, thus providing the necessary assurance of adequate response time to real–time constraints.
Since most of the subsystems to be connected don't have a CAN interface its necessary to use a CAN node interface. This consists in a small board with a microcontroller (such as 80594) that provides the interface between the sensor or actuator and the bus. The board has two parts: one responsible for communicating with the bus, and the other to interface with the device. This last part depends on the type of device: either serial port, or digital I/O or analogic with A/D.

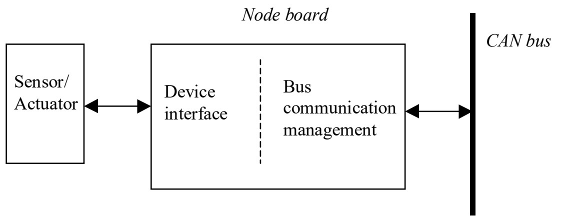

Fig. 5- CAN bus interface board.

One common example is a RS-232 /CAN gateway, that transfers messages between a standard RS-232 interface and CAN. These messages can be either commands or information.
The use of a CAN node can be extended to incorporate some processing of the messages received and issued to the devices, allowing in fact distributed processing whenever necessary, relieving the processing load of the main CPU.

Navigation system

The vehicle has a set of navigation and attitude sensors providing input data to the control system. These sensors comprise:

- Precision pressure depth cell.
- Magnetic compass (Precision Navigation TCM-2).
- Acoustic Doppler Velocimeter (allowing the measurement of inertial velocities).
- Optical encoders in each thruster.
- Inclinometers (included originally in the TCM2).

Additionally, an Inertial Motion Unit will be included to provide direct measurements of accelerations (Honeywell allow 6 acceleration’s measurement with high precision).
It is also integrate an acoustic positioning system to improve the navigation capabilities of the vehicle.

Inspection sub-system

The primary inspection sensor will be an underwater camera. This camera will be mounted in a pan & tilt unit to allow flexibility of inspection and possible compensation for some disturbances, which could not be taken care of in the movement of the vehicle.
In order to allow more room to accommodate the underwater connectors, the original lights that come with the vehicle lamps, are moved away from the top of the canisters to the front of the vehicle. On the pan&tilt unit, we have spotlights and, on the crash frame, flood lights.
This unit is a sub-Atlantic pan&tilt with a maximum payload of 40 kg.
The camera to be used will be a high sensivity camera and several models are being currently evaluated.
One problem, very common in the analysis of underwater video images is the notion of scale. The absence of some known size feature with which to compare sizes, and the need of measuring the observed features motivated the design of an additional device. This consists in two parallel fixed lasers mounted in the front of the vehicle. In this way, it appears, at close range, in the image 2 spots, which are at a known distance. This is only hold for planar walls and when the vehicle oriented perpendicularly to them. However, even in the other situations, it still provides some kind of scale measurement for the observed images.

An additional system to be considered is the inclusion of a pencil beam sonar located in the front of the vehicle. This sonar will provide not only additional inspection capabilities but also the measurement of the distance to the structure, thus enabling complex control manoeuvres such as keeping the vehicle at a fixed distance of the structure and moving within 2D surface.
Other types of sensors (and possibly actuators to remove the marine growth) are being evaluated.

Power sub-system

The power needed to operate the vehicle is delivered via the tether with 120 VDC. This is converted in the vehicle to the necessary voltages for the different subsystems (24V, 12V and 5V). This conversion is done by a power distribution module consisting on DC/DC converters and a monitoring power computer (a microcontroller embedded system). This power control system measures the consumption of the different sub-systems, and acts on the power supply of each system, allowing the controlled power off and on of the sub-systems. It is connected to the CAN network, receives commands from the central CPU and sends information about the system.
This allows the system to: be able to control the power up and power down sequence; restart some equipment that, for some reason, didn't booted up properly; and control the available power by changing its consumption according to the needs (e.g., turning-off some lights to provide more power to thrusters).

Cabling, electronics distribution and tether

The electronics in the vehicle are distributed in 3 pressure housings. Two are 9 cm diameter cylinders and the third is a 17 cm diameter cylinder. In the smaller cylinders are the power amplifiers for the thrusters, not only the forward ones but also the vertical and lateral thrusters.
There is also the power module and the necessary boards for communication with the central CPU.
In the figure 6, we can observe a simplified scheme for the initial configuration for the vehicle.
The larger cylinder has the PC104 stack with the CPU and the boards for communication with the surface. This is initially an ethernet link and it is intended to be replaced later on in the project by a fiber optic link. There is also the inertial navigation unit and the navigation sensors.
The necessary CAN interface nodes for external equipment such as control of the pan&tilt, camera, and the various sensors are placed in each cylinder according to the available space.
The video signal is fed directly to the umbilical chord and to the surface in a separated coaxial cable. Future versions will use a fiber optic link.

Thrusters and light control drivers

A drive circuit was installed in the vehicle for each of the four thrusters motor. The main goal of these drivers is to control the thrusters velocity in order to control the vehicle position, velocity and trajectory. Each drive circuit receives a CAN (Controlled Area Network) message from de main CPU with the information of the actuation that the thruster must perform. Therefore, when the main CPU sends an output control of 30% of the motor actuation, the driver circuit generates a PWM (pulse width modulation) of 30% and applies it to the motor. The driver circuit also sends information to the main CPU regarding the velocity and the current the motor.
As far as lights are concerned, the same principle was used to control the light intensity.

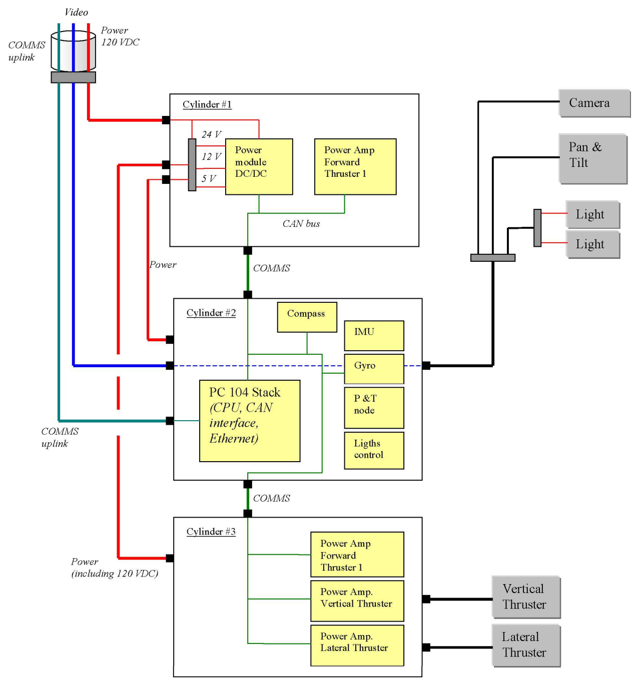

Fig. 6- Vehicle cabling and electronics.

Control architecture and software

The system is comprised of two distinct computational subsystems: one, at the surface, to interface with the operator, receive data and send commands to the vehicle, and, the other, on-board, responsible for the control.
The host target configuration is similar to the ones found in land-based robotic applications [4].
The on-board computer runs the real time operating system QNX. This operating system allows multiprocessing and provides the real time capabilities for the control of the vehicle.
The control architecture is a hierarchic layered one. While the lower level consists in a set of functionalities providing

the specified services, the higher levels are in charge of the overall coordination and organisation activities required for the mission success.
On the bottom, we have the necessary drivers to communicate with the sensors and actuators. These device drivers consist in low level processes and functions to access to the hardware.
On the top of these, we have the simple functionalities such as: fixing the rpm's of one thruster or measuring depth, etc… These allow the implementation more complex functionalities such as hovering or determining the vehicle position, etc…. On top of all of them, we have the coordination layer.

Host subsystem and human machine interface

The host computer performs high level tasks, which, in our system, are the interface with the operator devices (joysticks and controls) and the visualisation of data (in our case video signal).
The host computer runs a standard PC operating system and communicates through an ethernet link with the on-board system.
The human-machine interface is an important issue in achieving one of the main objectives of the project, the use of the system by a person with limited ROV training.
It has multimodal characteristics, in the sense that there are different and alternative views of the vehicle operation. This ensures flexibility in the design and ease of integration of new interfaces with the same vehicle. To support this, the host system has an interface server process that feeds the various interfaces with data from the vehicle and sends the commands to the vehicle. This must be done according to pre-determined access policies in order to prevent conflicting orders (only one operator can have the control).

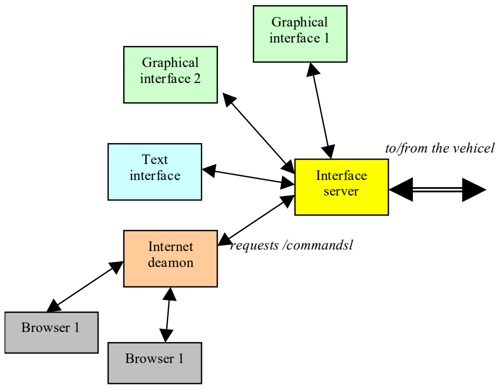

Fig. 7 – Host interface architecture.

One of the advantages of having an interface server process distinct from the actual interface consists in the possibility of controlling the system either from a simple interface on a laptop PC or from a complex multimedia interface on a large size computer equipped with virtual reality interfaces.

One of the clients of the interface server is an internet daemon that communicates through http and allows the direct visualisation of inspection data.
Other clients can be programmed to process, analyse, or simply, log data.

Conclusions and Future work

After an initial design stage, the project is now in the process of implementation. Most of the research effort is still ahead of us however, we are already benefiting from the time dedicated to the project requirement analysis and planning in the early stage of the project.
In spite of small deviations in scheduling of this project, due to some bad functions of some hardware components, the main hardware implementation objectives were attained.
The hardware system has been developed allowing for modularity. This feature is very important in a system where constant improvements must be made.
The acoustic system requires some improvement. With the modular architecture, its integration on the whole system is expected to be straightforward.
New types of inspection sensors should be investigated according to the envisaged inspection scenarios.

The next stage of this project includes the implementation of the control system.
Models of this type of vehicle were derived and the identification of their parameters should be sketched. In order to attain this objective missions should be planned to get data of vehicle behaviour. Non-linear control laws will be applied since models of this vehicle fall in this category. Lyaponov's laws, feedback linearization and sliding mode control are some of the control techniques to be implemented.
The implemented architecture encompasses a layer dedicated to trajectory generation. Its principles are based on hybrid systems theory. This architecture will allow the correct execution of the proposed manoeuvres.

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