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THE BRITE-EURAM III "REMOTE ROBOTIC NDT" RESEARCH PROJECT

Simone Reto, Giuseppe Casalino, Brian Bridge§

DIST - Department of Communications, Computer and System Sciences
University of Genova, Via Opera Pia 13, 16145 Genova, Italy

§ School of Electrical, Electronic and Information Engineering
South Bank University, 103 Borough Road, London, SE1 0AA, Great Britain

http://www.graal.dist.unige.it/~rrndt/web/rrndt.html

Abstract: the goal of this Brite-EURAM EC research project is to fulfil a need throughout industry for automated robotic systems that perform remote operations on large and complex vertical surfaces and ceilings with far more versatility and task repeatability than has been achieved hitherto. The final system will comprise of a compact-climbing vehicle that can move freely over large vertical areas carrying a manipulator with seven degrees of freedom. Such integrated device will be able to perform a variety of tasks (i.e. inspections, measurements, cutting, welding, polishing, etc...). This paper describes the whole project layout and the various compounding parts, including the system integration and the field trials with end-users expected performances.

Keywords: robotics, non-destructive inspection techniques, intelligent control.

Introduction

The international trend concerning the adoption of robots as a strategic technology is very evident, especially in the field of automated inspections and maintenance works in hazardous environments and unreachable sites such as chemical plants, nuclear power industries and large constructions. A clear industrial need has been recently identified for a mobile multi purpose inspection tool that can precisely carry out a whole range of inspecting tasks and maintenance procedures. Many automated systems presently available are tailored to do just one task and are equipped with robotics arm that have limited capabilities.

A multi-axis serial link robot manipulator is more flexible, with dexterity approaching that of a human arm. Many inspection tasks in industry are performed on large surfaces such as structural wall and ceilings (e.g. inspection of welds on the walls of nuclear pressure vessels and the hulls of large ships, the detection of wall thinning on petrochemical and process storage tanks, etc...).

Access to these inspection surfaces can be difficult and expensive due to remoteness, cramped conditions or a hazardous environment. Presently inspection in non-hazardous environments is done manually by climbing up the surface or by erecting expensive scaffolding. In hazardous sites, the inspection is automated with dedicated scanning devices that are limited to do a single specialised task.

The project goal is just the answer to all these industrial requirements. It will consist of:

- a compact and hybrid pneumatic climbing vehicle that can move freely on large surfaces, provide access to vertical walls and ceilings of large structures and is optimised for fast speed and large payload carrying capability
- a multi axis robot arm designed to perform inspection on almost any remote structural geometry with a variety of scanning routines, with similar dexterity to a human operator and deploy a variety of sensors and tools with far greater speed and spatial resolution
- accurate task control schemes for the scanning arm with the main objective of accurate and repeatable tracking of 3D trajectories which correspond to welded seams
- a flaw detector with a high level man-machine interface, incorporating advanced data processing and multi tasking computer technology to visualise data gathered by NDT sensors, to provide versatile and reliable real-time defect detection and reporting.

A definite area of application without much further modification of the project instrument is the civil engineering and construction industry, which has a need for remote inspection of all structures such as bridges, dams, chimneys, high rise buildings, etc...

The project started on 1st January 1997 and its end is expected on 31st December 2000. The EC have funded it within the BRITE/EURAM III, industrial and materials technologies program.

This paper will describe the project partnership in Section I. Then the system, as a whole, will be presented in Section II. The next Sections will describe the climbing vehicle, the manipulator and its controller and the Field trials, followed by some conclusions and comments.

1 PARTNERSHIP

Six partners located in three different nations (UK, Italy and Denmark) form the Project Consortium. In table I there is a summary of partners with their role within the project.

Organisation name	Country	Organisation business	R & D function
SBU	UK	University	NDT methods, development of climbing robot
OIS	UK	Inspection company	Instrumentation and field trials
ANSALDO	IT	Electromechanical company	Development of robot arm
OSS	DK	Ship building company	Evaluation of final system
ENEL	IT	Electricity company	Evaluation of final system
DIST	IT	University	Control system

Table I: Remote Robotic NDT Project Consortium

SBU (South Bank University) is one of the largest University in UK, with 16 schools and 5 faculties. The School of Electrical, Electronic and Information Engineering (EEIE) is one of the most important provider of taught courses of its kind in the UK, with 75 staff people. School research programmes include software engineering, design of electronic measurements circuits and systems, digital signal processing, mathematical modelling, control and robotics, sensor design and material testing.

OIS Plc is one of the largest technical inspection organisations within Europe. The company employs approximately 1400 personnel and its principal operating locations are in the UK, Middle East and South Africa. Its core business activities are in the field of Non-Destructive-Testing, where it provides services to the power generation, petrochemical, process plant, offshore, fabrication and pipeline market sectors.

ANSALDO is one of the major integrated electromechanical engineering groups world-wide; it is part of Finmeccanica in the IRI Group, and employs 20,000 people in more than 20 production facilities. For over 20 years, its NUCLEAR DIVISION has been involved in the design, development, manufacture and installation of specialised remote handling equipment for nuclear power plants. Special skills are deployed in the design of mechanism and telemanipulators to be used in hostile environments and critical safety situations.

OSS (Odense Steel Shipyard), member of the A.P. Moller Group of Companies, is among the most modern and efficient shipyards in the world. Founded in 1917, the shipyard has continuously expanded and modernised. Recent designs include container vessels, product/chemical carriers, LPG tankers, bulk carriers, supply vessels and anchor handling/fire fighting tugs.

The aim of **ENEL** is to carry on, within the Italian territory and with economical criteria, the activities of production, import and export , transport, transformation and sale of electrical energy, produced from any kind of source. ENEL covers about 83% of Italian energy requirements, and it is the third largest company in the world, after the French and British National Authorities.

DIST, the Department of Communications, Systems and Computer Sciences of the University of Genova-Italy, has been established in 1984. Since then it has developed a long research tradition within the fields of Industrial Automation, in general, and Robotics in particular. DIST has been involved in many EC projects, starting from the very early ESPRIT project 595 on CIM for large welded fabrications, passing through the TELEMAN project No 8, the basic research ESPRIT projects FIRST and SECOND, to finally end with the MAST project AMADEUS on submarine robotics.

2 SYSTEM DESCRIPTION

As disclosed in the introduction, three parts form the system: the vehicle, the arm and the ultrasonic probe, plus the system controller including the man-machine interface

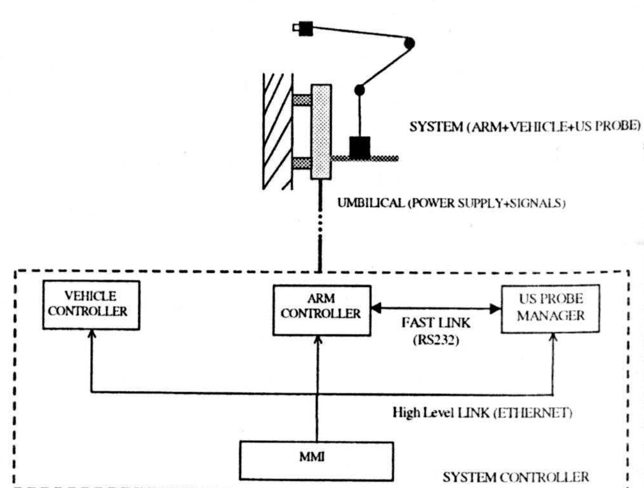

Figure IIa: Whole system layout

In figure IIa the system layout is depicted, presenting its main components.

The man-machine interface runs on a PC. It manages the interaction with the operator and the links with the three subsystems, co-ordinating their distinct operating modalities. When a task to be performed is chosen by the operator (via graphical interface), the MMI first sends commands to the vehicle controller. This operation is achieved using the high-level link, based on an ethernet connection and the TCP/IP protocol. When the vehicle reaches the correct position, the MMI makes the arm and the ultrasonic probe working. These subsystems need to communicate at a higher rate with respect to the high-level link and with real-time constraints. Hence a link based on an asynchronous serial RS-232 line has been established. During the task execution, both subsystems communicate with MMI, especially the probe one, which sends the acquired data to be visualised on the PC screen (i.e. C-scan, P-scan, etc...).

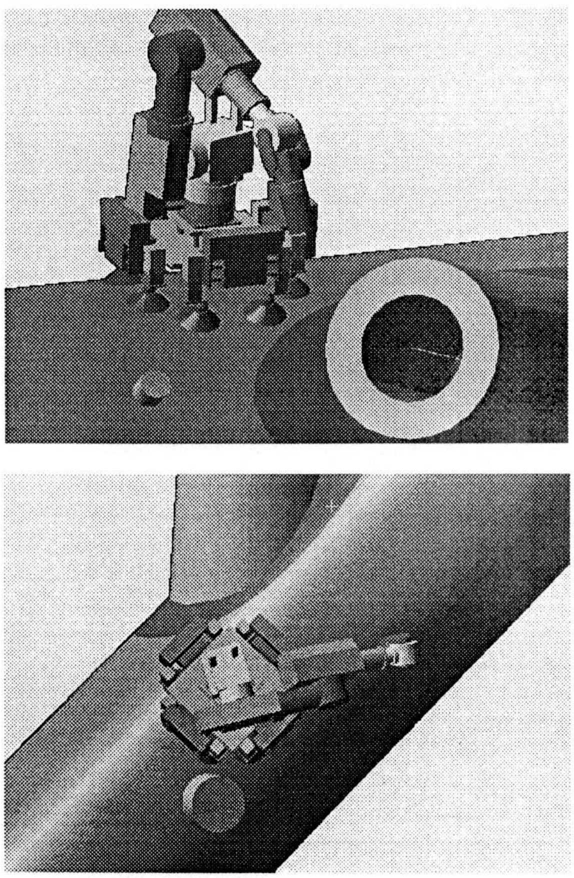

Figure IIb: Side and Top view of the system (CAD simulation)

From the mechanical point of view, in figure IIb two CAD pictures are placed, showing the arm arrangement on the vehicle. These images are taken from a simulation of the inspection concerning the expected field trial at OIS (see section VI).

Concluding, here it is a list of key features of the system:

- Overcome surface irregularities such as rivet heads, welds, etc.
- Climb on wet or rust surfaces.
- Operate for up to 10 hours at temperatures between -10 to +50 °C.
- Achieve safety through a dual lane fault tolerance system that can withstand power supply, HW or SW faults.
- Work in open air.
- Operate in radioactive environment or environment with fumes.
- Operate with control equipment placed at distances of up to 30 m.
- Be placed/attached /adjusted to the inspection surfaces in less than 10 minutes by one/two operators.
- Operate from a wide ranging AC power supplies e.g. 80V to 24V (50-60 Hz).
- Locate and mark detected defects
- Get defect information about location, size, etc... displayed on the man-machine interface

3 CLIMBING VEHICLE

The climbing vehicle is an eight-legged mobile platform based on pneumatic technology, developed by SBU[1]. The choice of using suction cups has been taken because of the stainless steel construction used in PWRs, which are one of the target inspection sites. In table IIIa the features of the mobile vehicle are listed. Four main aspects are considered as remarkable:

- Lightweight
- Compactness
- High payload
- Ability to cope with curve surfaces

Weight	23~25 Kg
Size	360 x 360 x 190 mm
Max. climbing height (arm mass: 30 Kg)	18 m (safety factor 2)
Max. payload (on-board plus umbilical)	30 Kg (safety factor 2)
Stride (max)	60 mm
Maximum climbing speed	1 m/min
Travelling way	Along X-Y directions
Compressor air pressure	8-12 bar (boosting)
Umbilical	30 m
Umbilical weight	< 0.5 Kg/m
Max. available force (per actuators pair)	1.153 N at 6 bar
Feet cup size	100 mm (diameter)
Feet cup material	Rubber NPV50
Max. friction force per side foot cup	260 N on steel plate

Table IIIa: vehicle features

All of these requirements have been satisfied in order to accomplish the end-user requirements concerning the foreseen final trials. The mechanical and electronic part design has been kept very simple as well, considering this aspect as another key feature for the project. In particular, the chassis dimensions have been limited due to the specification given by OSS for the shipyard inspection. In such case there is the presence of a passage hole with dimensions of 400x600 mm. Besides, the design of lockable ankles has been carried out considering the OIS inspection task., with the

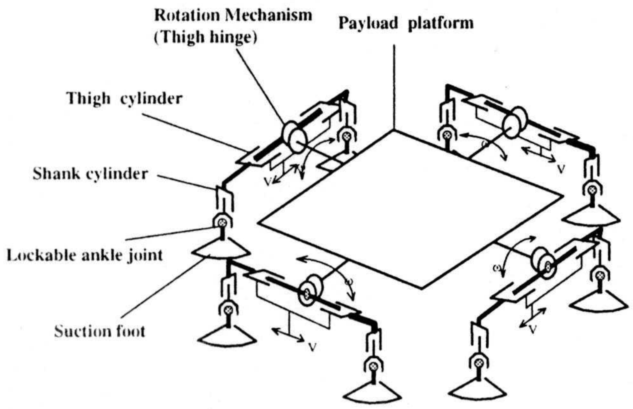

Figure IIIa: vehicle basic design

presence of a pipe of 1 m as diameter. The particular choice in foot design (see Figure IIIa) gives the vehicle the ability to cope with such curve surface, greatly enhancing the system versatility. The vehicle will be able, in fact, to travel on concave surface with a minimum diameter of 3 m and convex surface with a minimum diameter of 1m. Surfaces can also be wet or rust

It is also important to remark the good compromise obtained between the constraint of lightweight and high payload required. The first is necessary in order to help the operators when carrying the system to the inspection site. The second feature is related to the arm and umbilical weight, as they have to be carried by the vehicle itself.

4 MANIPULATOR

The manipulator design has been performed taking into account the following basic points (according to the industrial requirements stated in the Introduction):

- Light weight
- Reliability
- Compatibility with severe environmental conditions
- Easiness of maintenance

In order to accomplish to the above mentioned design guidelines, Ansaldo has designed a manipulator based on few off-the-shelf components set in a global architecture whose simplicity allows for easy maintenance. This solution also allows for the

Joint	Joint Name	Joint Speed	Joint Workspace
1	Turret	30°/sec	± 170°
2	Shoulder	30°/sec	± 170°
3	Elbow Roll	45°/sec	± 180°
4	Elbow Pitch	45°/sec	± 150°
5	Wrist Roll	90°/sec	± 180°
6	Wrist Pitch	90°/sec	± 120°
7	Hand Roll	90°/sec	± 180°

Table IVa: arm kinematic features

minimisation of the arm weight, increasing concurrently the reliability due to a simple design. Lightweight has been obtained through the utilisation of light alloys and minimising the arm structure thickness. The unavoidable problem of backlash presence in the gearing trains has been faced adopting pre-loaded gears on the end shafts of each joint. Such pre-load has been achieved by means of Belleville springs or using the motor support natural flexibility. Motors have been chosen because of their small size and high torque at a relatively low speed (3000-rpm). This solution assures a prompt response due to the small ratio of the gear trains. In order to improve the maintainability and global reliability of the arm, another feature of the arm is that all cables (power and signals) are rooted inside the arm itself.

The kinematics and the architecture of the arm are depicted in figure IVa. The main features are: 7 dof and high level of dexterity in a compact size. The expected total mass of the manipulator is less than 22 Kg. The payload will be about 40 N with an accuracy of 1mm

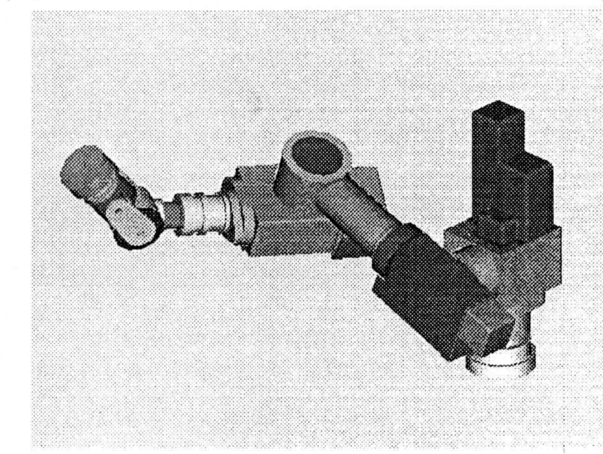

Figure IVa: arm layout

approximately. The length of the forearm is 300 mm, while the arm length is 310 mm. Joint actuation will be performed by brushless motors provided by WacoGiken (equipped with brake and incremental encoder).

The manipulator consists of four subassemblies: turret, shoulder, elbow and wrist. The turret includes the turret and the mechanical and electrical interface with the vehicle. A motor connected to a reduction unit and a couple of gears drive the joint. This is provided with a potentiometer which constantly measures the absolute position of the joint referred to the mechanical interface of the vehicle even after a power loss. The electrical interface consists of four waterproof connectors set at the base of the arm. The wrist consists of a roll-pitch-roll movement, whose driving lines are coaxial positioned into the forearm, which also includes the three driving motors of this subassembly. A JR3 force/torque sensor is placed between the wrist and the ultrasonic probe interface. It is used to control the contact force of the end-effector, allowing the surface contouring during the inspection tasks. All the cables are optimised as far as the number of wires and their dimensions are concerned.

To achieve an arm mass as light as possible, special materials are going to be used. In particular the arm body will be manufactured using aluminium high-strength alloy, while the internal gears will be made in titanium alloy grade 5. All components which are not particularly stressed (i.e. cover plates) will be manufactured in suitable plastic material. The aluminium alloy components will be sheltered by anodization. Bearings will be bought sealed and for-life lubricated. Special greases will be used for gear lubrication, in order to increase the time interval between two maintenance stages.

5 ARM CONTROL

The arm will be controlled using a hierarchical, two-layered family of algorithms. The following figure

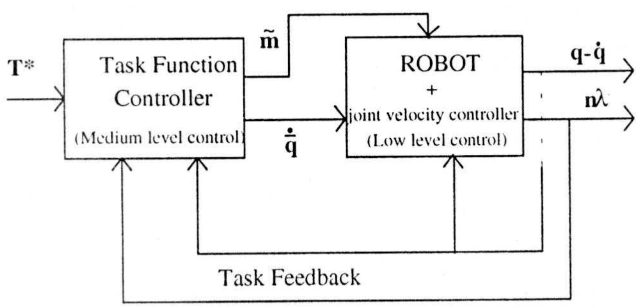

Fig. Va Task Function Based Control Approach

will sketch the basic concepts of this approach:

The task function approach to the control has been introduced **[2]** in 1991 by Espiau. It is based on the idea of computing an error quantity, which represents a distance from the task completion state. The controller is designed to lead the error in a zero-state point of equilibrium, so that the task will be terminated when the error approaches to zero. Complex and multi-robot co-ordinated tasks may be accomplished as well, using this approach, simply scheduling (either dynamically or off-line) sequences of task functions.

The task function controller computes a task error, on the basis of the task command T* (i.e. position/orientation/contact force reference values coming from the system controller) and the task feedback measured from the manipulator. The controller uses the task error to compute the medium level motion control law in terms of desired joint velocities:

Our motion control approach **[3-5]** (both position and orientation of the end-effector, both free and constrained) is of kinematic and hierarchical type (as seen in figure Va). In fact the motion task function controller (medium level) produces a joint velocity command, which can be considered as the low level reference command. The low-level control law is characterised, being the implementation of a hybrid motion-contact force controller, by two terms. One is the joint velocity servoing torque contribution while the other is given by the constrained interaction control.

The ARM controller will be VME based. We have a VME rack (with a 6U 6 slots backplane) like the one in figure Vb. The MVME162 are popular Motorola CPU boards with an IP carrier on-board. We will use piggyback modules (on CPU B) to perform I/O operations related to the manipulator controller (typically read encoders and ADCs, write DACs and manage digital I/O). The actuators are 7 Waco Giken AFS4.

CPU A	CPU B	JR3 REC.	IP CARR.	FREE	FREE	ETH. MOD	CONNECT.	ACTUATORS

Figure Vb: Arm controller HW description

The medium level controller will run on CPU A, plus the tasks which manage the communications (with MMI by mean of TCP sockets and with probing system by mean of serial line). The low level controller will run on CPU B, implementing a digital joints velocity servoing, as explained above. A secondary IP carrier board is used to host modules with digital I/O. The JR3 receiver is a DSP-based board that allows the CPU boards to retrieve the measured values of the contact force/torque already filtered and processed simply reading VME memory locations

The operating systems used on the CPU boards is VxWorks™, the well-known real-time O.S. by WindRiver. A friendly, powerful, safe and effective tool for the rapid prototyping of control systems has been also development as preliminary stage of the project. In fact the need of designing, simulating, testing and implementing more and more complex control schemes is growing quickly. This tool will allow testing several different approaches, comparing the performances in a very short time, both via simulation and via direct implementation.

The environment chosen is the very well known and world-spread MATLAB™ package with its Simulink and Real-Time-Workshop toolboxes. Simulink is the tool devoted to the simulation of dynamic systems and it is based on a very easy-to-use graphical interface; besides it gives the chance to the user to add to the system custom blocks containing C code compliant with a given template. The RTW is a tool that, working jointly with a real time development system (like the WindRiver's Tornado), produces C code ready to be compiled, downloaded and executed on a multi-tasking real-time platform.

6 FIELD TRIALS

The general objective is to perform field trials that will prove the adaptability of the robotic inspection tool to the real physical "environment". The demands set up in the specification task will be demonstrated to be achieved through trails on the inspection application of the end-users. The specified applications are five:

- OIS: Ultrasonic examination of set in nozzle welds
- OSS: Testing of start/stop sequences in panel welding
- OSS: Testing of shell plate welding in the dock assembly area
- OSS: Testing of welds in 3D-sections
- ENEL: Inspection of Pressure Vessels

In each of the above tests, the system will have to detect welding defects after a scanning procedure, with graphical output and disk storage of the collected data.

Conclusions

The "Remote Robotic NdT" project has been presented in this paper, starting from the motivation lying at the base of the proposal and ending with a description of the field trials which are expected to be performed during year 2000.

Even if the project is not strictly related to the field of automation in construction, particular emphasis has been given to all the aspects that could certainly be of interest in such discipline. In particular the features of the vehicle, of the arm and of the control methods, which could be easily adapted to the execution of many tasks in that field, with great enhancements in terms of accuracy, time and costs savings.

Acknowledgements

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