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A cost-effective robotic solution for the cleaning of ships' hulls

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SUMMARY

Hull cleaning before repainting is a key operation in the maintenance of ships. For more than a decade, a means to improve this operation has been sought through robotization and the use of different techniques such as grit blasting and ultra high pressure water jetting. Despite this, it continues to be standard practice in shipyards that this process is carried out manually. This paper presents a family of robots that aims to offer important improvements to the process as well as satisfying, to a great extent, all the operative requirements of efficiency, security, and respect for the environment that shipyards nowadays demand. It is described the family of devices with emphasis on the mechanical design. This set consists of two vertical robotic towers and a robot climber. In addition, it is shown the control architecture of the global system. Finally, operative results are presented together with a comparison between the performance achieved in shipyards through the use of these robots and those obtained with a manual process.

KEYWORDS: Service robots; Ship repair industry; Grit blasting.

1. Introduction

In the same manner as much industrial machinery, every four or five years ships are taken out of service to perform periodical maintenance. One of the most important operations consists of the elimination of rust and marine material that has adhered to the hull, with the aim of preparing the surface for later repainting. This operation is carried out to conserve the integrity of the hull and thereby guaranteeing suitable sailing conditions. Maintaining the surface of the hull in good hydrodynamic conditions means a reduction in fuel consumption, and therefore a reduction in atmospheric pollution. The most widely used technique for the cleaning of ships' hulls,[1,2] and the preferred by most ship owners, consists of open-air blasting of the hull with metallic grits (see Fig. 1). This technique achieves the optimal SA $2\frac{1}{2}$[3] surface finish for the hull, which assures good paint adherence and prolongs the periods between further repainting. The ultra high pressure (UHP) water jetting[4] does not achieve the same surface finish. Furthermore, the robotized systems based on this technology are too expensive to be widely accepted by shipyards.

In spite of the advantages, grit blasting technology is not very environmentally friendly. This is due to the fact that it is carried out in open air and generates a great deal of residuals in the form of dust that is dispersed into the atmosphere, the area surrounding the shipyard and even the sea. This powder contains a mixture of paint, full of heavy metals and biocides, as well as fragments from the blasting process (pyrite, silica sands, etc.). For this reason, open-air grit blasting is forbidden in European countries with strict environmental requirements and clear indications that it will be banned definitively in the rest of Europe. This means that ship owners are transferring this work to shipyards in countries where open air grit blasting is still allowed (Eastern countries, Korea, China, etc.), with the consequent economic losses for Europe.

The robotization of these tasks using reusable grit blasting material, working in a closed cycle and enclosing the hull area that is being cleaned, is a problem that has no easy solution. Cleaning operations take place in areas with a great number of obstacles (cranes, rails, scaffolding, sheds, maintenance teams, cables, propellers, etc) and with surfaces of hull with very different forms and sizes. All these factors make the design of robotic devices intended for general use difficult.

The cleaning of large vertical surfaces has a simpler solution. For some time, robots for cleaning this type of surface either with water[5] or with grit[6] have been available, resulting in a very high standard of work although at a substantial cost.

In addition to this, robotic solutions based on robotic climbers have existed for some time. However, they all use high-pressure water jetting technology, which curbs their use for the reasons previously mentioned. Among the systems currently available it is worth mentioning the system developed by Ultrastrip Systems, Inc[7]. This vehicle is built of aluminium and titanium and is attached to the hull by the combined use of a magnetic head and a vacuum system. Perhaps it is the most efficient system but it is expensive and uses water jetting. It is also worth mentioning the Hydro-Crawler system developed by Dans Vandteknik,[8] the HydroCat system of Flow International Corporation,[9] and Octopus system of Cybernetix.[10]

This article presents a family of low-cost robotic devices that are used for grit blasting, with emphasis on the mechanical design. They obtain a high-quality surface

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Fig. 1. Working conditions of the traditional blasting process.

finish (SA $2\frac{1}{2}$) while simultaneously reducing drastically the amount of residual material produced. In addition, this family of robots has been designed with a spotting operation capability in mind. Spotting consists of grit blasting small areas of the hull where defects, sometimes as small as a coin, have been found. Given the budget limitations of ship owners, spotting is a common form of hull maintenance.

The different robotic systems presented in this article have been developed within the framework of the environmentally friendly and cost-effective technology for coating removal (EFTCoR) project,[11] and are the result of the combined efforts of shipyards, manufacturers and research centers. In Section 2, the design criteria imposed by the shipyards are presented. Two types of devices have been defined according to these criteria: robotic vertical towers and a robotic climber. The following sections offer in detail, from a mechanical point of view, the different devices that constitute the family of robots. Section 3 describes the vertical towers while Section 4 describes the robotic climber. In Section 5 the control architecture of the global system is discussed. Finally, in Sections 6 and 7 the operative results are presented together with a comparison of the achieved results.

2. Shipyard Requirements and General Solution Outline

The mechanic design criteria that need to be born in mind when automating this type of maintenance operations should take into account the following functional requirements imposed by the shipyard:

- In order to obtain the best surface finish, and to avoid the problems of rusting that high-pressure water jet cleaning can cause, grit blasting should be the principle technique used for cleaning.
- The quantity of dust which escapes into the atmosphere should be as small as possible. This means that the grit blasting area needs to be enclosed, and a method of suction needs to be used that collects the grit as well as the resulting residuals.
- The quantity of residuals generated should be minimized, in order to lessen the problems resulting in their collection, transportation, and storage. This requirement obliges the use of a grit which can be reused a certain number of times, and to incorporate elements of grit collection, residual separation, temporary storage, and recirculation.
- The recyclable grit material must have the mechanical properties needed to obtain a surface quality at least as good as that obtained with disposable grits. These properties should deteriorate as little as possible during the cycles of reuse. The grit should also be reasonable priced.
- The dimensions and shapes of the ships differ greatly due to their hydrodynamic features. There may also be different types of obstacles on the surface of the hull (portholes, rivets, deformations due to collisions, reinforcement plates, etc.).
- The working conditions differ in relation to the part of the hull being cleaned (keel, bottoms, bow and stern shapes or vertical surfaces). The facilities provided by shipyards may also differ in this point (e.g., dry dock or elevators of the Synchrolift type, see Fig. 2).
- From an operational point of view, there are two working modes, "full blasting" and "spot blasting". "Full blasting" consists of blasting the entire hull of the ship, while the "spot blasting" consists of blasting numerous isolated areas where corrosion has been observed. "Full blasting" requires robotic devices capable of positioning big cleaning heads that move over the entire hull surface with the aim of obtaining a high standard of work. "Spot blasting", on the other hand, requires robotic devices that can position small cleaning heads quickly and with adequate precision.
- The robotic systems should be flexible enough to carry out other maintenance operations, such as fresh water cleaning and painting.

The importance of each one of these requirements is relative, and depends on the working culture, policy, and priorities of the shipyard in question. Therefore, any solution oriented to the client, such as that presented in this paper, needs to

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a) Bottom. Synchrolift. b) Bow shape. Synchrolift.

c) Vertical surface. Dry dock.

Fig. 2. Possible ship working environments.

be sufficiently flexible to meet their requirements. It will also condition the design approach of the different robotic systems. Table I summarizes the main requirements imposed by two important European shipyards. As can be seen, not all of these requirements coincide.

These requirements can be roughly summarized into (1) the two different working modes (full blasting and spot blasting), (2) the different areas of work (vertical, fine and bottom), and (3) the need to reduce costs. Due to the wide variety of the requirements set by shipyards, it has been impossible to design a solution based on the use of a single robot. Rather, the solution that has been adopted is based on combining different robotic systems, as is presented in Table II.

All these systems consist of a primary positioning system of, at least, three degrees of freedom, an optional secondary element (mounted on the primary system), and a cleaning head that can be either a grit blasting turbine or a grit blasting mouthpiece with a confinement hood.

3. Vertical Robotic Towers

The **first of the robotic towers** has been developed for the Navantia shipyard in Cartagena and relies on a Synchrolift system[12] to carry out the docking of the ship before its maintenance. The Synchrolift is a ship lift, as shown in Fig. 3. As it can be observed, the dimensions of the lift limit the size of the ship that can be raised. In the case of this lift, ships that exceed 150 m in length, 25 m in beam, and 9 m in draft cannot be lifted.

Once the ship has been raised with the aid of Synchrolift and is moved to an appropriate place in the shipyard, the robotic tower is used to carry out the maintenance operations (see Fig. 4). The tower has a load capacity of 500 kg at the tip of the arm, a height of 12 m (*Z*-axis), and can move on rails along the whole length of the hull (typically 100 m in *X*-axis). In the same way, the cleaning head can move approximately 2 m in the *Y*-axis in order to adapt to the shape of the ship. The tower also has two additional degrees of freedom to guide either a large cleaning head for full blasting or a *XYZ* table for spotting (see Fig. 4) according to the shape of the hull. The load capacity is a critical parameter. To increase load capacity means to increase the size and weight of the tower, as well as the power of the motors, that in turn means to increase the cost of the tower. It has been a design objective to balance these parameters providing the tower with both enough load capacity and performance, but maintaining its weight and dimensions, as well as its cost, as low as possible.

The tower is composed of a strong vertical structure (Fig. 4–01), of around 4 m in width, by 2 m in depth, and 12 m in height. A substructure in the form of a basket slides within the vertical structure (Fig. 4–02) with the aid of a lift. This movement is achieved through the help of a hoist system of elevation that only needs 1.5 kW to operate (Fig. 4–03), with four steel cables (Fig. 4–04) and with the structure counterbalanced (Fig. 4–05). A truss is mounted upon this mobile substructure by means of an arm (Fig. 4–06), of a cross-section of 0.6 × 0.6 m and of approximately 2 m in length. This arm is folded by means of two revolving wheels and at the end there is a folding flat base, which is needed to hold the cleaning head (Fig. 4–07). With this configuration, it is possible to move the cleaning head along the shaped parts of the hull in reduced places. Cleaning head is moved by the combined motion of the basket (linear up and down) and the

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Table I. Requirements imposed by two shipyards.

Requirements	Shipyard 1 Synchrolift system	Shipyard 2 dry dock
Costs	*Not more than the current costs including salaries*	*Same or improved in comparison to the costs of conventional techniques, the cost of the abrasives should also decrease*
Benefits	*5 m^2/man - hour* *Efficiency of the mouthpiece 10 m^2/hora*	*Not numerically quantified*
Environmental	*Reduction in dust emissions of at least 70%*	*The quantity of abrasive used should drastically decrease*
Working area	*Synchrolift* *Very narrow space between ships, the elimination of obstacles in the work area presents an organizational problem*	*Dry dock* *Very large work area, but available space limited*
Capacity to adapt to the different working modes ("full blasting" and "spot blasting")	*"Spot" makes up 80% of the works.*	*"Spot" makes up 35% of the work and 48% of all blasting work*
Quality of surface finish	*SA 2 1/2 (ISO 8501-1)*	*SA 2 1/2 (ISO 8501-1)*
Capacity to adapt to other maintenance work	*Fresh water cleaning, painting*	*Fresh water cleaning, painting*
Capacity to adapt to different types of ships and shapes of hulls	*Ships up to:* *125 m in length* *25 m depth* *23 m width* *Great variability as far as shape is concerned*	*Tankers up to 300 m Great deal of vertical surfaces*
Ease of operation	*Should be capable of being operated by low qualified personal*	*Should be capable of being operated by low qualified personal*
Possibility of automation	*Yes*	*Yes*
Other	*Possibility of on line access for the quality control department*	*Easy to transport and to mount*

arm (circular motion). Neither in dry docks, where the hull is extremely closer to walls, nor in Synchrolift systems, where ships are usually "parked" too close together, there is enough space behind the tower to use a linear axe to move the tool away from the hull.

In the Fig. 4 photograph, this arm is holding a cleaning turbine, while in Fig. 5 it holds a *XYZ* table. The tower is self-propelled by means of a motorized platform, with two 1.1 kW gearmotors mounted in its base (Fig. 4–10). In this way, it is able to move on rails parallel to the hull of the ship (Fig. 4–11). The weight of the combined unit reaches some 20 tons.

An *XYZ* table (see Fig. 5) has been developed as a **secondary element** that allows spotting work to be carried out. This cleaning head moves at a speed of 1 m/s for grit blasting positioning and 0.2 m/s during the actual process of grit blasting. This XYZ table is built of a framework of 80 × 80 mm aluminium profiles (Fig. 5–01), of dimension 2700 × 2000 mm, on which are mounted five electro-mechanical linear cylinders without rods, activated by servomotors with braking control: two for the *X*-axis (Fig. 5–02), and a longitudinal travel of 1500 mm. It is mechanically linked with a drive axle (Fig. 5–03); two for the *Y*-axis (Fig. 5–04), with a longitudinal travel of 1500 mm; and one for the

Table II. Maintenance operation and devices developed in the context of the EFTCoR project.

	Hull area under consideration		
Cleaning operation	Vertical surfaces	Fine	Bottom
Full blasting *Large surfaces*	*Primary system: vertical* *Head: turbines*	*Primary system: vertical towers* *Head: nozzle* *Primary system: climbing vehicle* *Head: nozzle*	*Primary system: elevator table* *Head: turbine* *Primary system: climbing vehicle* *Head: nozzle*
Spotting *Small multiple surfaces scattered over the underwater body*	*Primary system: vertical towers* *Secondary system: XYZ table* *Head: nozzle*	*Primary system: vertical towers* *Secondary system: XYZ table* *Head: nozzle*	*Primary system: elevator table* *Secondary system: XYZ table* *Head: nozzle*
	Primary system: climbing vehicle *Head: nozzle*	*Primary system: climbing vehicle* *Head: nozzle*	*Primary system: climbing vehicle* *Head: nozzle*

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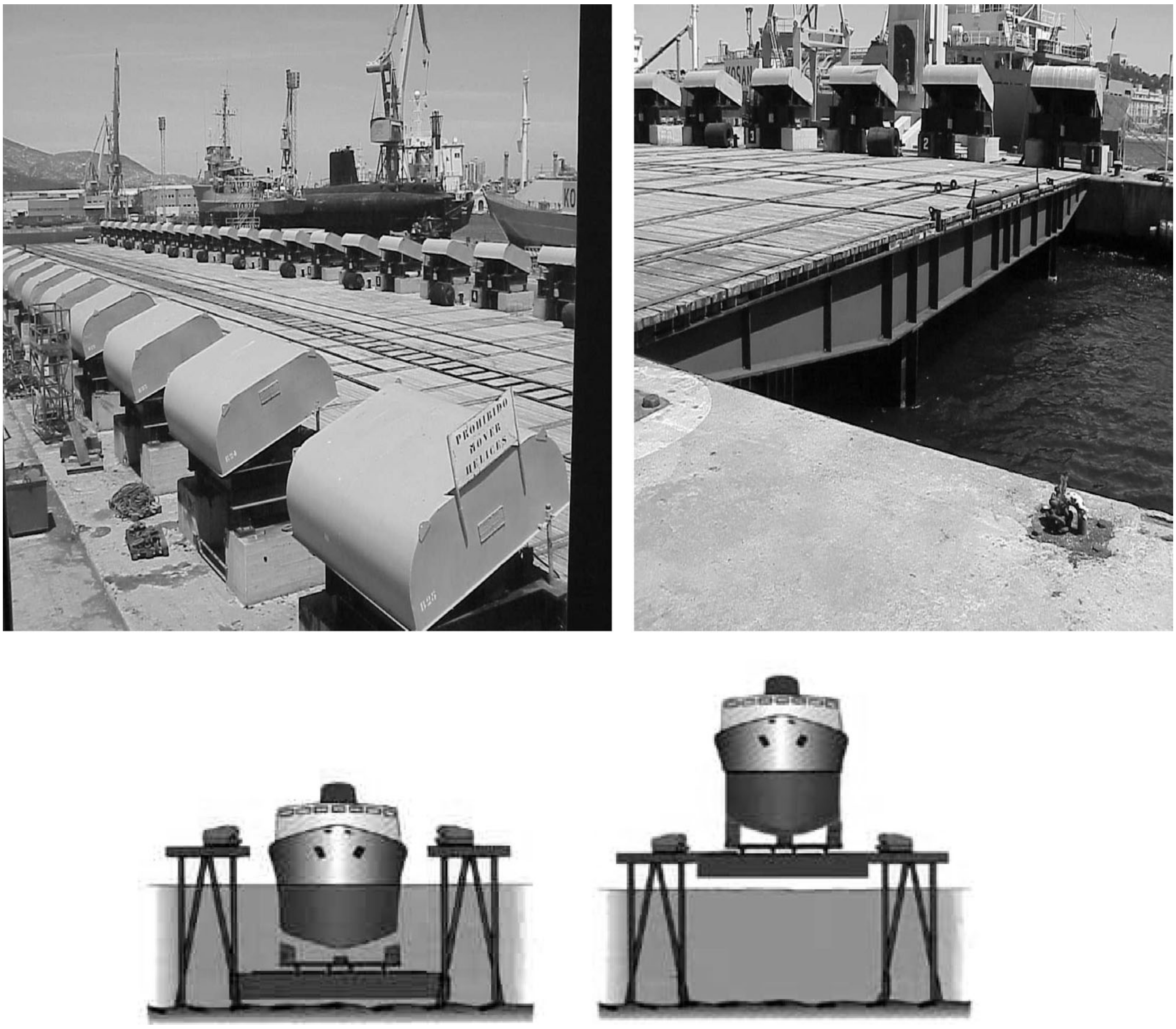

Fig. 3. Synchrolift: system for lifting boats and ships out of the water for maintenance work or repair (Length: 150 m, Width: 25 m, and Height: 15 m).

Z-axis (Fig. 5–05), with a longitudinal travel of 400 mm. The movement is achieved on all axes by means of a ball screw. At the far end of the *Z*-axis the secondary system is installed, which consists of a blasting hood (Fig. 5–06), with the grit inlet (Fig. 5–07), and the suction outlet (Fig. 5–08). The gritting hood is supported by a shock absorbing structure (Fig. 5–09) that assures a firm contact between the hood and the surface of the hull. For the computer vision system a camera enclosed within a watertight casing (Fig. 6–10) is placed on a specially adapted mounting bracket (Fig. 6–11) and fixed to the same frame as the *XYZ* table. The weight of the whole assembly ascends to approximately 500 kg.

The **second of the towers** has been developed for the Navantia shipyard in Ferrol and has been installed over a dry dock (see Fig. 6). With a load capacity of up to 1000 kg, it has a height of 25 m and it can move approximately 300 m on rails set into the floor. This tower has a similar morphology to the tower previously mentioned, but it is higher. It is composed of a strong vertical structure (Fig. 6–01), with an internal sliding substructure (Fig. 6–02), also guided in the manner of a lift. This substructure has a basket shape and slides by means of a hoist elevation system, with four steel cables (Fig. 6–04), and counterweight (Fig. 6–05). The secondary system (*XYZ* table) is mounted directly onto this mobile substructure (Fig. 6–06). This tower is also self-propelled, by means of a motorized platform, with two gearmotors (Fig. 6–07) mounted in its base, and is able to move, parallel to the hull of the ship, on rails (Fig. 6–08). This tower works very close to the hull of the ship, at about 250 mm, and does not have a trusswork arm, since it has been used only to perform spotting in vertical surfaces. Nevertheless it has enough load capacity to be provided with a trusswork arm to carry out blasting in shaped areas.

4. Robot Climber

The robot climber consists of a vehicle (see Fig. 7) that adheres magnetically to the hull, capable of moving at a speed of 0.5 m/s without gritting and 0.2 m/s when grit blasting. The climber has a load capacity of 10 kg. It is mainly used to gain access to those parts of the hull that the rest of the system cannot reach either because of obstacles, lack of space or the shape of the ship.

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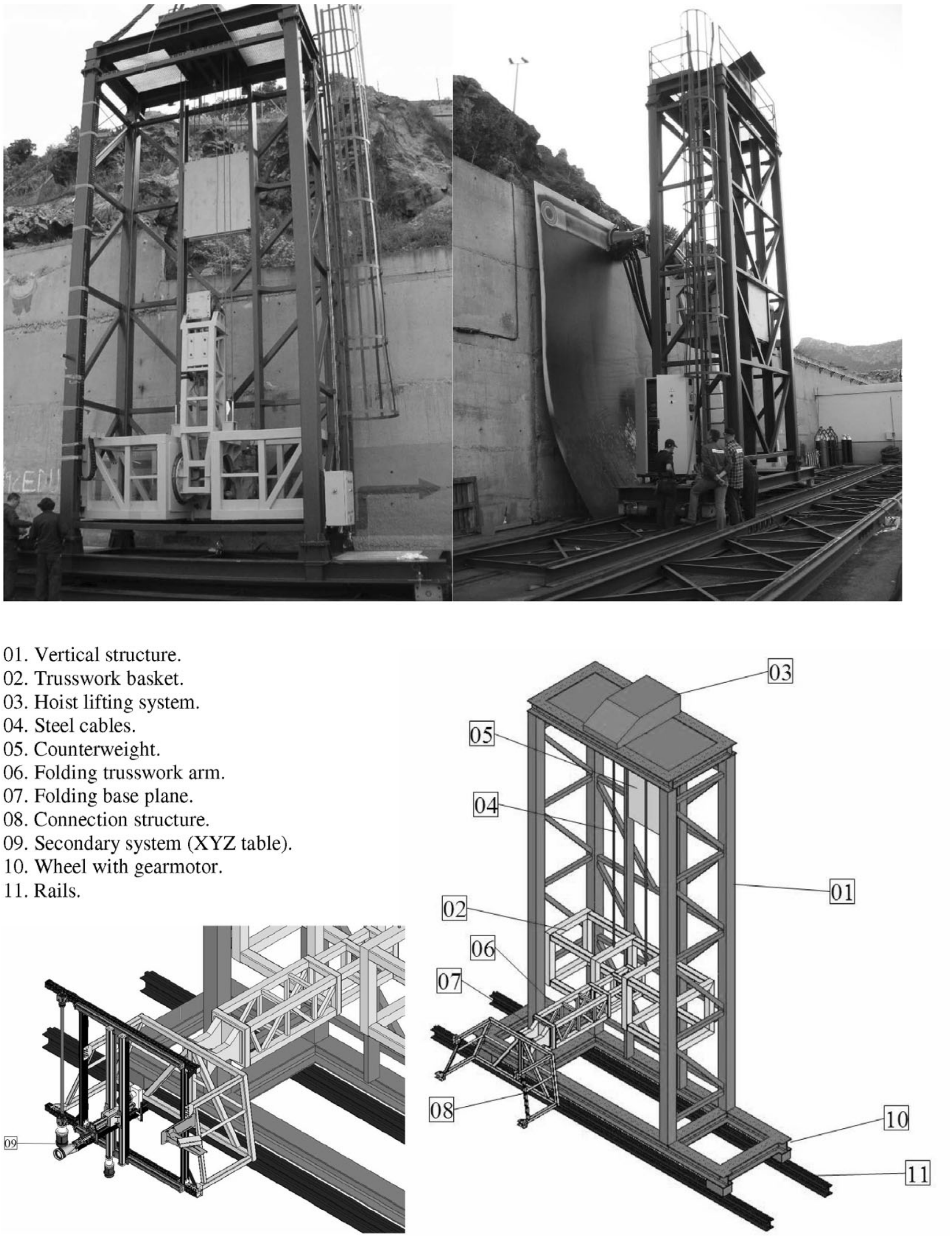

Fig. 4. Robotized tower with articulated arm for Synchrolift system.

The vehicle consists of two 1.57 kW AC servomotors (Fig. 7–01) of 3000 rpm, 5 Nm, each with braking control, and planetary differential relationship $i = 10$, mounted lineally in an opposed way, which drive on two gear aluminium wheels (Fig. 7–02) covered with double toothed polyurethane belts (Fig. 7–03). The vehicle has a mounting bracket structure (Fig. 7–04) which is, in the central section, expandable and adaptable to the different sizes of the blasting hood (Fig. 7–05). This hood has a grit entry (Fig. 7–06) and a suction confinement inlet (Fig. 7–07). As it has already been mentioned, the vehicle adheres magnetically to the hull of the ship by means of 16 permanent square magnets of neodymium (Fig. 7–08) of 55 × 55 × 15 mm, which are enclosed within stainless steel boxes. These are distributed homogeneously throughout the whole vehicle, and generate an excellent capacity of magnetic attraction. There are two automatic limit switches (Fig. 7–09), which maintain a superficial contact with the hull and which, in the event of accidental separation of the vehicle, cut the grit flow. Also, to avoid the climber accidentally falling to the ground, the vehicle is equipped with two security devices connected to metallic belts (Fig. 7–10). The weight of the whole assembly amounts to about 70 kg. It has been tested using two kinds of grit for blasting, copper slag (1 mm grain) and steel grit (1 mm grain), and using an air pressure of 8 bar. When using steel grit, the vehicle relies on the capacity of the cleaning head and suction system to retrieve the grit. Grit losses are usually small (about 3 %), but they suppose a serious problem since grit adheres to magnets or (after being magnetized) to other parts of the vehicle.

As far as we know, the robot climber presented here is the only one that uses grit instead of high pressure water. It is

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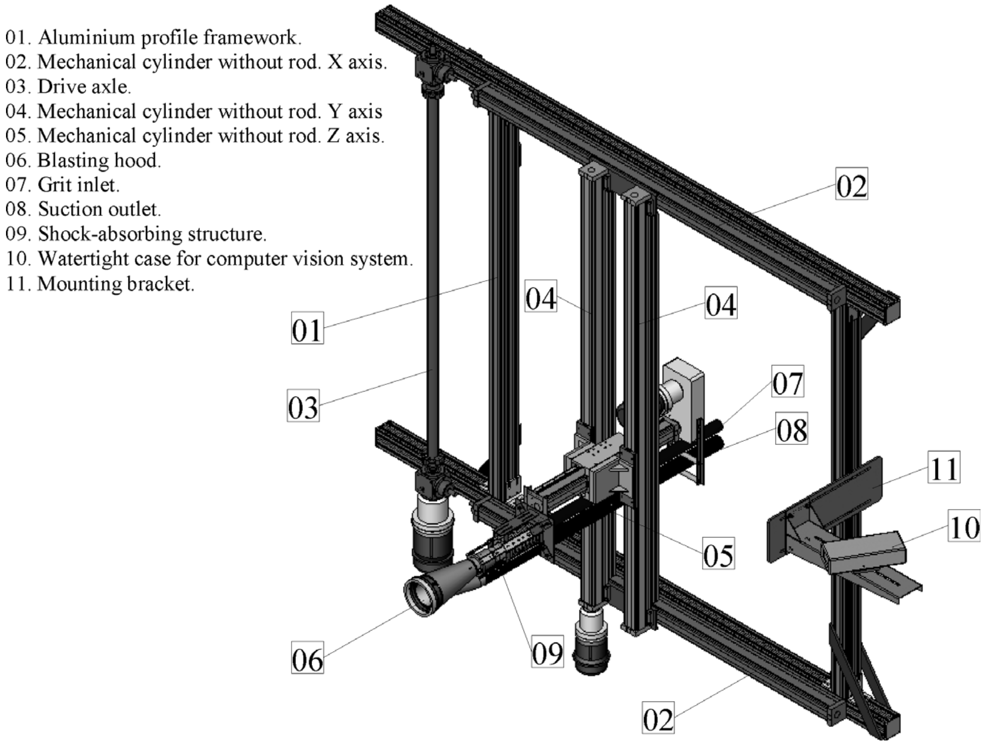

Fig. 5. Details of the robotized tower with *XYZ* table.

not an industrial vehicle yet, like Ultrastrip System,[7] but it is reliable and efficient enough to demonstrate the feasibility of using the grit technology in a climbing robot.

5. Control Architecture

Besides the low cost robotic devices already described, the system proposed in this paper also consists of the following elements (see Fig. 8):

- A control unit for each robot, adapted to the functions and tasks that are to be carried out. Specifically, the control unit of the climber vehicle is an industrial PC fitted with RT LINUX, while the control units of the towers are based on more conventional control based automatic machinery, mainly Programable Logic Controllers (PLCs). Each control unit has its own man–machine interface, some of which are simple while others are very sophisticated. The control units can receive commands from the local interfaces of the teleoperation platform or from external systems such as that of the computer vision system, depending on the operational mode.
- Computer vision systems that inspect the surfaces of the hull, determine the areas to blast, provide the route that each robot should follow and check the final quality of the blasting work. The features of each visual system are different, according to the robot under consideration. For instance, in the case of the articulated crane, it is advantageous to align the tool according to the contours of the hull, while in the case of spot blasting with the XYZ table the visual system determines the dot matrix to blast. The visual system is described in ref. [14].
- A teleoperation unit for each robot, tailored to its functionality and teleoperation scheme. For example, in the case of the XYZ table, an industrial PDA by which the operator can select the area to blast through the use of a graphic interface. In this case, the teleoperation unit calculates a grit blasting matrix and sends it to the control unit.
- A supervision platform that includes a CAD system with the data of the ship that it is being worked on, and the progress of the work that is being carried out (surface grit blasting, grit consumption, operation time, etc). The platform is able to supervise and to coordinate up to ten robots, thereby optimizing the quality of the finished work and the operation times. It also provides services such as planning, work-flow and jet operation simulation, data base system management, control of operators, etc.[13]

All these elements are organized according to a global architecture that is structured hierarchically into the following three levels (see Fig. 8):

- **The highest level corresponds to the monitoring system.** This level is in charge of the global management of the maintenance tasks for the ship. It is an information system that allows managers to dispatch cleaning tasks to local teleoperation platforms, and to monitor the performance levels of each robot (cleaning times, grit consumption, energy consumption, etc.). With the aid of this system, the managers can decide the best configuration for every work to be performed. It is, above all, a work-flow tool.
- **The intermediate level corresponds to the teleoperation platforms.** This is an adaptation and extension of a previously designed platform for teleoperating service robots in nuclear power plants.[15] Their development is

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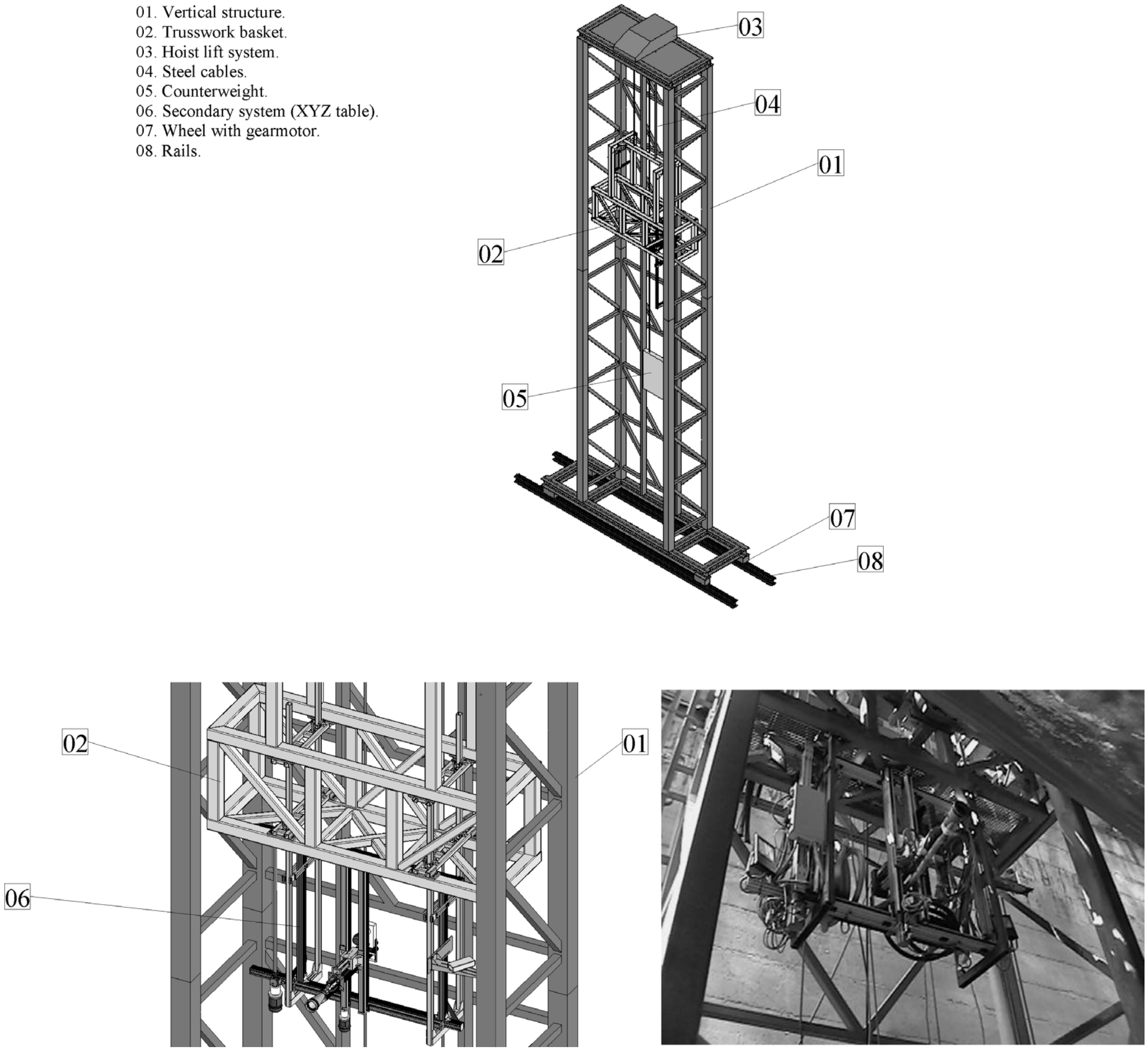

Fig. 6. Dry dock tower with secondary system mounted (*XYZ* table).

based on the use of a reference architecture that was designed using domain engineering.[16] Nevertheless, this existing architecture had to be adapted due to the fact that in the original systems the robots were totally teleoperated, while some of the robots described in this paper have a level of decision and autonomy relatively high. This level receives the cleaning tasks dispatched by the monitoring system. With the aim of facilitating the work of the operator, the insertion of commands at a very high level has been permitted. These commands are executed in the local control units of each robot.

- **The inferior level corresponds to each one of the local control units of the service robots.** Each control unit has its own architecture adapted to its functionality, from pure teleoperation to very high levels of autonomy. This aspect represented a new technological challenge, in the sense of being able to reuse complete functional blocks in robots with very different control architectures. This led us to develop an architectural framework to design control units (ACROSET),[17] in which a fundamental aspect is the use of advanced concepts of software engineering, especially the component based development paradigm.[18]

This global architecture is a purely hierarchical one, where commands flow from the higher levels to the lower ones (from the monitoring system to each teleoperation platform, and from each teleoperation platform to the local control unit of each robot), and where data flows in the opposite direction, in order to provide managers and operators with the data they need to carry out their duty (performance data and control data, respectively). It is also highly parallel, as there could be many robots, working concurrently. The system as a whole is not autonomous, as robots do not actively cooperate, but rather wait for cleaning instructions. Cleaning tasks are manually decided and dispatched at the central monitoring system, and each teleoperation platform is simply in charge of cleaning the selected areas. Nevertheless, we are currently working on an enhanced version of the towers that

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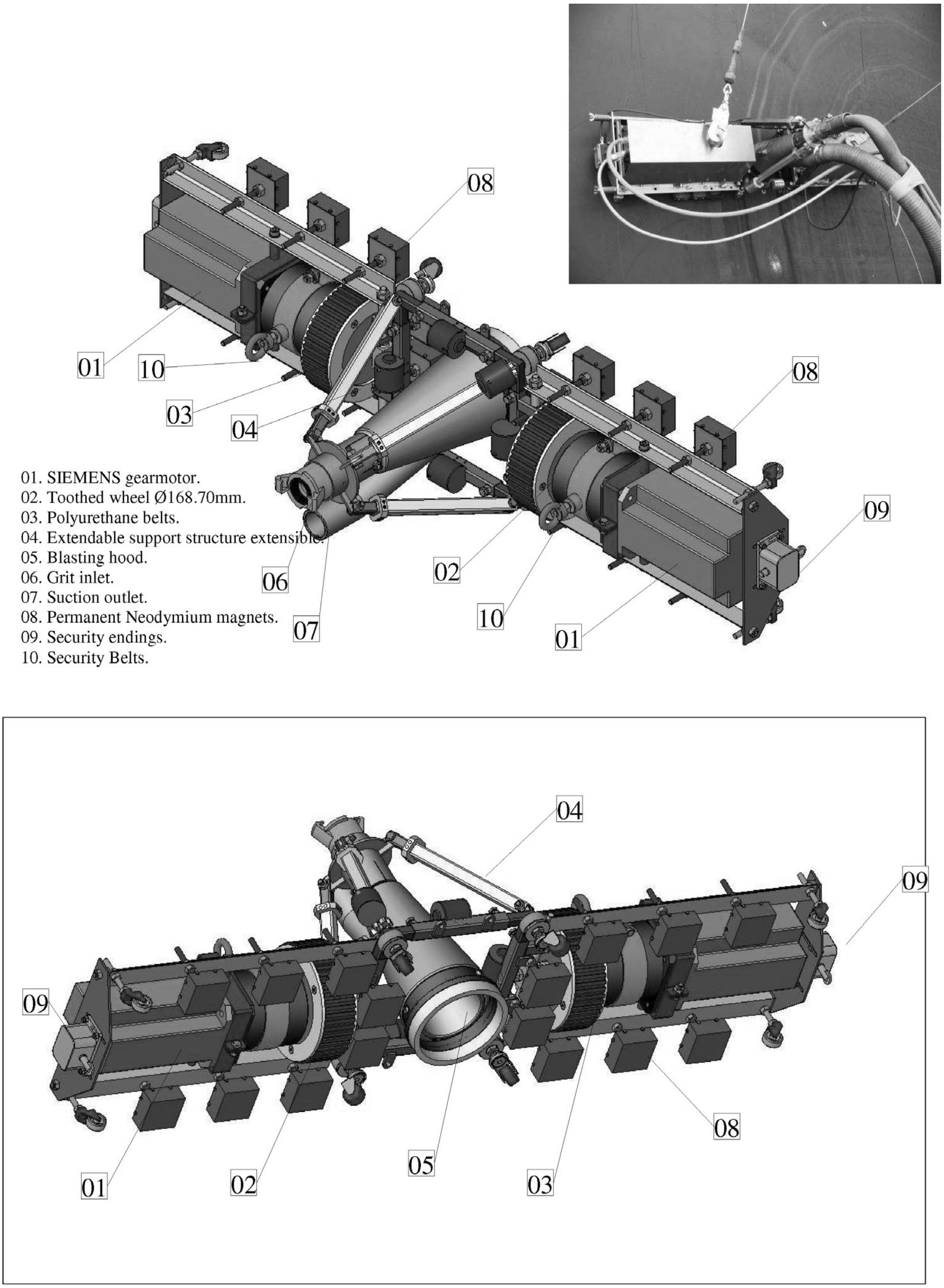

Fig. 7. Climbing Vehicle, top and bottom views.

will carry several cleaning tables, and which will thus need a certain degree of cooperation among them. A higher degree of cooperation will also be needed when working with several towers or climbing vehicles, but this depends on budget of the shipyard and its needs. In any case, this architecture is flexible enough to accommodate these kinds of requirements. In fact, some of the pointed out cooperative strategies have been simulated, but none of them, until now, has been put into practice.

The engineering effort has aimed above all to integrate existing solutions and software tools in order to provide a robust and efficient solution. The control at a servo level of the aforementioned robotic devices is relatively simple. The main complication comes with the integration of very

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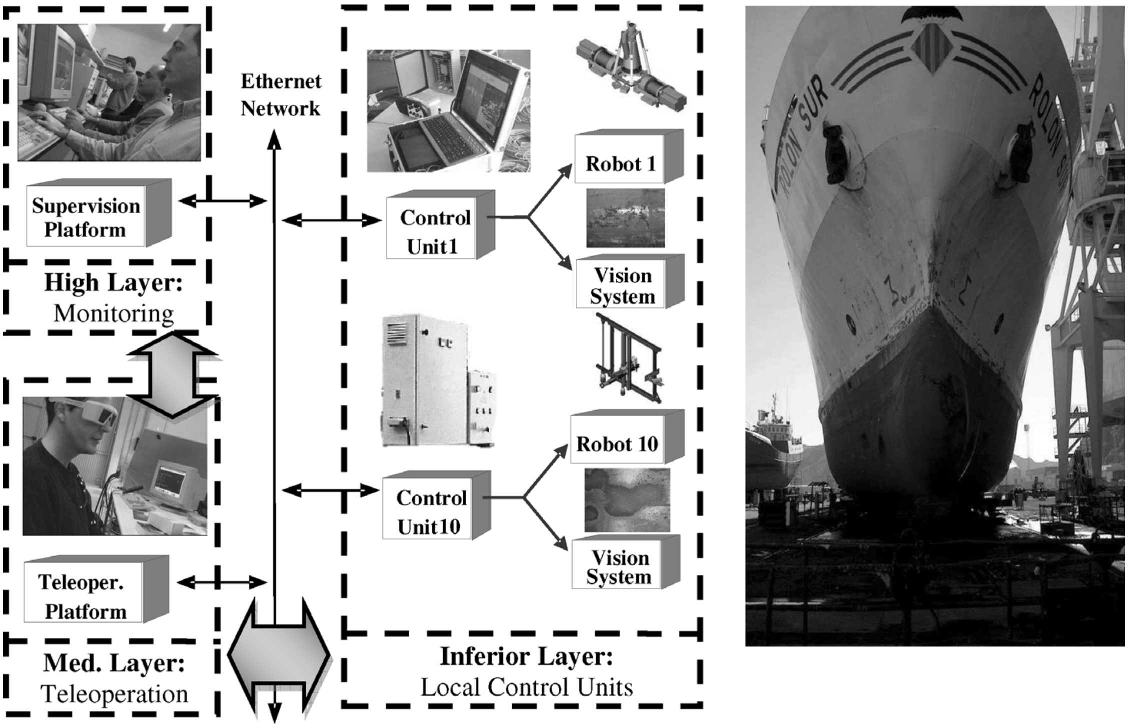

Fig. 8. Global outline of the EFTCoR system. The figure depicts the three layers the global architecture has been divided into, together with the data and command flow among them (big grey filled arrows). It is also remarkable that the whole system is linked by means of an Ethernet network.

diverse software components (computer vision system for the control unit under consideration, relations to the higher levels, synchronism with external systems such as that of the recycling, sensorial systems, local control of axis and tools, etc.). Our concern is not only with what is done but also with how it is done. Hence our interest in applying state-of-the-art software engineering paradigms (software architectures,[19] component oriented programing[20] and model driven engineering.[21])

6. Evaluation of the Benefits

All the EFTCoR devices have been tested in the Navantia shipyards in Ferrol and Cartagena under real conditions (three months in Cartagena and three weeks in Ferrol with actual ships).

In order to evaluate the benefits of the EFTCoR robots, it is necessary to bear in mind the type of ship used in the tests, and the type of installation where they were carried out. Table III details the most important characteristics of the ships in the shipyards where our robots were evaluated. As can be seen, the sample is sufficiently representative that the results obtained can be generalized to any other type of shipyard. Table IV summarizes the results achieved with the family of robots EFTCoR in the two reference shipyards, and the comparison of these results with the parameters obtained using the usual manual procedure. The parameters that have been recorded are those related to the hourly and total efficiency (included downtimes), as well as the costs. It is possible to appreciate important differences between each shipyard due to the different working environments, as well as the fact that the methods used are very different (dry dock in Ferrol, Synchrolift in Cartagena). However, even with the worst results, the robotic systems achieved the same efficiency as the manual operations and, as can be seen in the table, sometimes made notable improvements. The total (m^2/day) efficiency has improved significantly when the regular breaks in work, that are necessary in manual operations due to the demanding working conditions, are removed from the results.

Even in cases where the total efficiency is similar to that of manual operation, the system maintains the advantage of operating within a closed cycle, separating the residuals as well as reusing the grit. This represents a real improvement as an environmental friendly technology when compared to the more traditional techniques.

The costs shown in Table IV include the costs of the grit. Using a more expensive (T-GRIT®) abrasive, the costs actually decreases because of the fact that thanks to the recirculation system it can be reused up to 200 times. Labour costs also decrease.

7. Conclusions

This article has given details of a series of service robots for hull cleaning that work together in order to offer solutions to problems that currently concern the European ship repair industry.

The prototypes developed in the EFTCoR project are open systems, intended to be combined in such a way as to accord with both the needs of the operation to be carried out, and to integrate support subsystems of control and navigation. For example, to carry out spotting on a vertical surface the

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Table III. Characteristics of the ships according to shipyard.

Shipyard	DWT[a] (Ton)	Beam (m)	Depth [b] (m)	Length (m)	Height (m)
Navantia (Cartagena, Spain)	Until 5500	23	9	125	25
Navantia (El Ferrol, Spain)	5,000–340,000	15–70	4–25	70–360	NA

[a] Deadweight Tonnage.
[b] (from the keel to the flotation line).

Table IV. Comparison of manual – automatic results.

		Shipyard			
		Navantia Cartagena		Navantia Ferrol	
Evaluated Parameter		Full	Spot	Full	Spot
Hourly efficiency	Manual	25 m^2/hour	17.5 m^2/hour	180 m^2/hour	NA
	EFTCoR	30 m^2/hour	22.3 m^2/hour	180 m^2/hour	35 m^2/hour
Total efficiency	Manual	400 m^2/day	290 m^2/day	1500 m^2/day	NA
	EFTCoR	540 m^2/day	325 m^2/day	1500m^2/day	620 m^2/day
Costs	Manual	8.1 €/m^2	10.7 €/m^2	NA	NA
	EFTCoR	7 €/m^2	9 €/m^2	7 €/m^2	9 €/m^2

prototype uses a computer vision system that automatically generates the matrix of the areas that need to be blasted.

The automated *XYZ* table and computer vision system combination solves most of the technical uncertainties associated with the automation of the spotting process on vertical surfaces; however, it does present a number of shortcomings in terms of performance, security and user-friendliness. Among the shortcoming of the EFTCoR prototypes it is essential to highlight the following points:

- The current prototype is able to carry out a semiautomatic process of cleaning in a previously selected length of hull. However, a semiautomatic process of cleaning in larger stretches of hull (at least in the vertical areas of the hull and preferably in the entire hull) would be advantageous.
- It is necessary to provide the system with a higher level of autonomy in order to allow it to automatically recognise any hull defect and undertake consequent blasting.
- Robots are not fully autonomous. The central monitoring system divides and assigns the working areas to each robot manually. It would be desirable to make this process semi-automatic, and to provide the robots with a certain level of autonomy, enabling them to cooperate in order to fulfil the cleaning tasks.
- The achieved performance levels for the robots are similar (and clearly better in some cases) to those achieved by human operators. It would be desirable to enhance the designs in order to increase performance, for instance, by incorporating additional secondary systems (XYZ table) to the primary element (tower) in order to decrease spotting times.

These points correspond to typical prototype shortcomings due to the fact that priority is given to overcoming specific technical problems, and factors such as costs, maintenance, and reliability of the systems are not given the same consideration. Work is currently underway to solve these problems. We have currently received funds of the Spanish Government (PET 2008–0131) to carry out this task jointly with Spanish Technological Centers and SMEs with the objective of enhancing the design of the robots in order to increase their performance levels, and to make them robust enough to market an industrial product.

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