

# 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,<sup>1,2</sup> 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<sub>1/2</sub><sup>3</sup> surface finish for the hull, which assures good paint adherence and prolongs the periods between further repainting. The ultra high pressure (UHP) water jetting<sup>4</sup> 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<sup>5</sup> or with grit<sup>6</sup> 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<sup>7</sup>. 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,<sup>8</sup> the HydroCat system of Flow International Corporation,<sup>9</sup> and Octopus system of Cybernetix.<sup>10</sup>

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.

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

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

## 115 2. Shipyard Requirements and General 116 Solution Outline

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

- 121 • In order to obtain the best surface finish, and to avoid the  
 122 problems of rusting that high-pressure water jet cleaning  
 123 can cause, grit blasting should be the principle technique  
 124 used for cleaning.
- 125 • The quantity of dust which escapes into the atmosphere  
 126 should be as small as possible. This means that the grit  
 127 blasting area needs to be enclosed, and a method of suction  
 128 needs to be used that collects the grit as well as the  
 129 resulting residuals.

- The quantity of residuals generated should be minimized, 130  
 in order to lessen the problems resulting in their collection, 131  
 transportation, and storage. This requirement obliges the 132  
 use of a grit which can be reused a certain number of times, 133  
 and to incorporate elements of grit collection, residual 134  
 separation, temporary storage, and recirculation. 135
- The recyclable grit material must have the mechanical 136  
 properties needed to obtain a surface quality at least 137  
 as good as that obtained with disposable grits. These 138  
 properties should deteriorate as little as possible during 139  
 the cycles of reuse. The grit should also be reasonable 140  
 priced. 141
- The dimensions and shapes of the ships differ greatly 142  
 due to their hydrodynamic features. There may also 143  
 be different types of obstacles on the surface of the 144  
 hull (portholes, rivets, deformations due to collisions, 145  
 reinforcement plates, etc.). 146
- The working conditions differ in relation to the part of the 147  
 hull being cleaned (keel, bottoms, bow and stern shapes 148  
 or vertical surfaces). The facilities provided by shipyards 149  
 may also differ in this point (e.g., dry dock or elevators of 150  
 the Synchrolift type, see Fig. 2). 151
- From an operational point of view, there are two 152  
 working modes, “full blasting” and “spot blasting”. “Full 153  
 blasting” consists of blasting the entire hull of the ship, 154  
 while the “spot blasting” consists of blasting numerous 155  
 isolated areas where corrosion has been observed. “Full 156  
 blasting” requires robotic devices capable of positioning 157  
 big cleaning heads that move over the entire hull surface 158  
 with the aim of obtaining a high standard of work. “Spot 159  
 blasting”, on the other hand, requires robotic devices 160  
 that can position small cleaning heads quickly and with 161  
 adequate precision. 162
- The robotic systems should be flexible enough to carry out 163  
 other maintenance operations, such as fresh water cleaning 164  
 and painting. 165

The importance of each one of these requirements is relative, 166  
 and depends on the working culture, policy, and priorities 167  
 of the shipyard in question. Therefore, any solution oriented 168  
 to the client, such as that presented in this paper, needs to 169

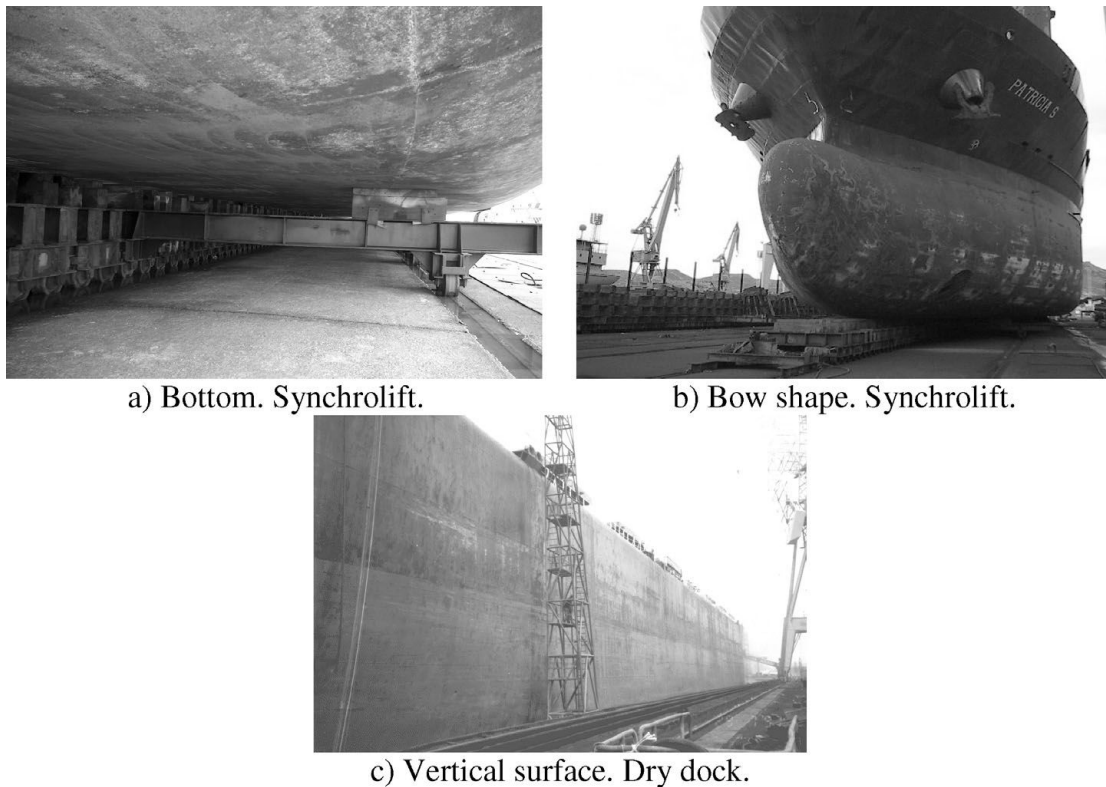


Fig. 2. Possible ship working environments.

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

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

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

### 189 3. Vertical Robotic Towers

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

198 Once the ship has been raised with the aid of Synchrolift  
 199 and is moved to an appropriate place in the shipyard, the

200 robotic tower is used to carry out the maintenance operations  
 201 (see Fig. 4). The tower has a load capacity of 500 kg at the tip  
 202 of the arm, a height of 12 m (Z-axis), and can move on rails  
 203 along the whole length of the hull (typically 100 m in X-axis).  
 204 In the same way, the cleaning head can move approximately  
 205 2 m in the Y-axis in order to adapt to the shape of the ship. The  
 206 tower also has two additional degrees of freedom to guide  
 207 either a large cleaning head for full blasting or a XYZ table  
 208 for spotting (see Fig. 4) according to the shape of the hull.  
 209 The load capacity is a critical parameter. To increase load  
 210 capacity means to increase the size and weight of the tower,  
 211 as well as the power of the motors, that in turn means to  
 212 increase the cost of the tower. It has been a design objective  
 213 to balance these parameters providing the tower with both  
 214 enough load capacity and performance, but maintaining its  
 215 weight and dimensions, as well as its cost, as low as possible.

216 The tower is composed of a strong vertical structure  
 217 (Fig. 4-01), of around 4 m in width, by 2 m in depth, and  
 218 12 m in height. A substructure in the form of a basket slides  
 219 within the vertical structure (Fig. 4-02) with the aid of a  
 220 lift. This movement is achieved through the help of a hoist  
 221 system of elevation that only needs 1.5 kW to operate (Fig. 4-  
 222 03), with four steel cables (Fig. 4-04) and with the structure  
 223 counterbalanced (Fig. 4-05). A truss is mounted upon this  
 224 mobile substructure by means of an arm (Fig. 4-06), of a  
 225 cross-section of  $0.6 \times 0.6$  m and of approximately 2 m in  
 226 length. This arm is folded by means of two revolving wheels  
 227 and at the end there is a folding flat base, which is needed to  
 228 hold the cleaning head (Fig. 4-07). With this configuration, it  
 229 is possible to move the cleaning head along the shaped parts  
 230 of the hull in reduced places. Cleaning head is moved by the  
 231 combined motion of the basket (linear up and down) and the

Table I. Requirements imposed by two shipyards.

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

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

237 In the Fig. 4 photograph, this arm is holding a cleaning  
238 turbine, while in Fig. 5 it holds a XYZ table. The tower is  
239 self-propelled by means of a motorized platform, with two  
240 1.1 kW gearmotors mounted in its base (Fig. 4–10). In this  
241 way, it is able to move on rails parallel to the hull of the ship  
242 (Fig. 4–11). The weight of the combined unit reaches some  
243 20 tons.

244 An XYZ table (see Fig. 5) has been developed as a  
245 **secondary element** that allows spotting work to be carried  
246 out. This cleaning head moves at a speed of 1 m/s for grit  
247 blasting positioning and 0.2 m/s during the actual process of  
248 grit blasting. This XYZ table is built of a framework of 80  
249 × 80 mm aluminium profiles (Fig. 5–01), of dimension 2700  
250 × 2000 mm, on which are mounted five electro-mechanical  
251 linear cylinders without rods, activated by servomotors with  
252 braking control: two for the X-axis (Fig. 5–02), and a  
253 longitudinal travel of 1500 mm. It is mechanically linked  
254 with a drive axle (Fig. 5–03); two for the Y-axis (Fig. 5–  
255 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.

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

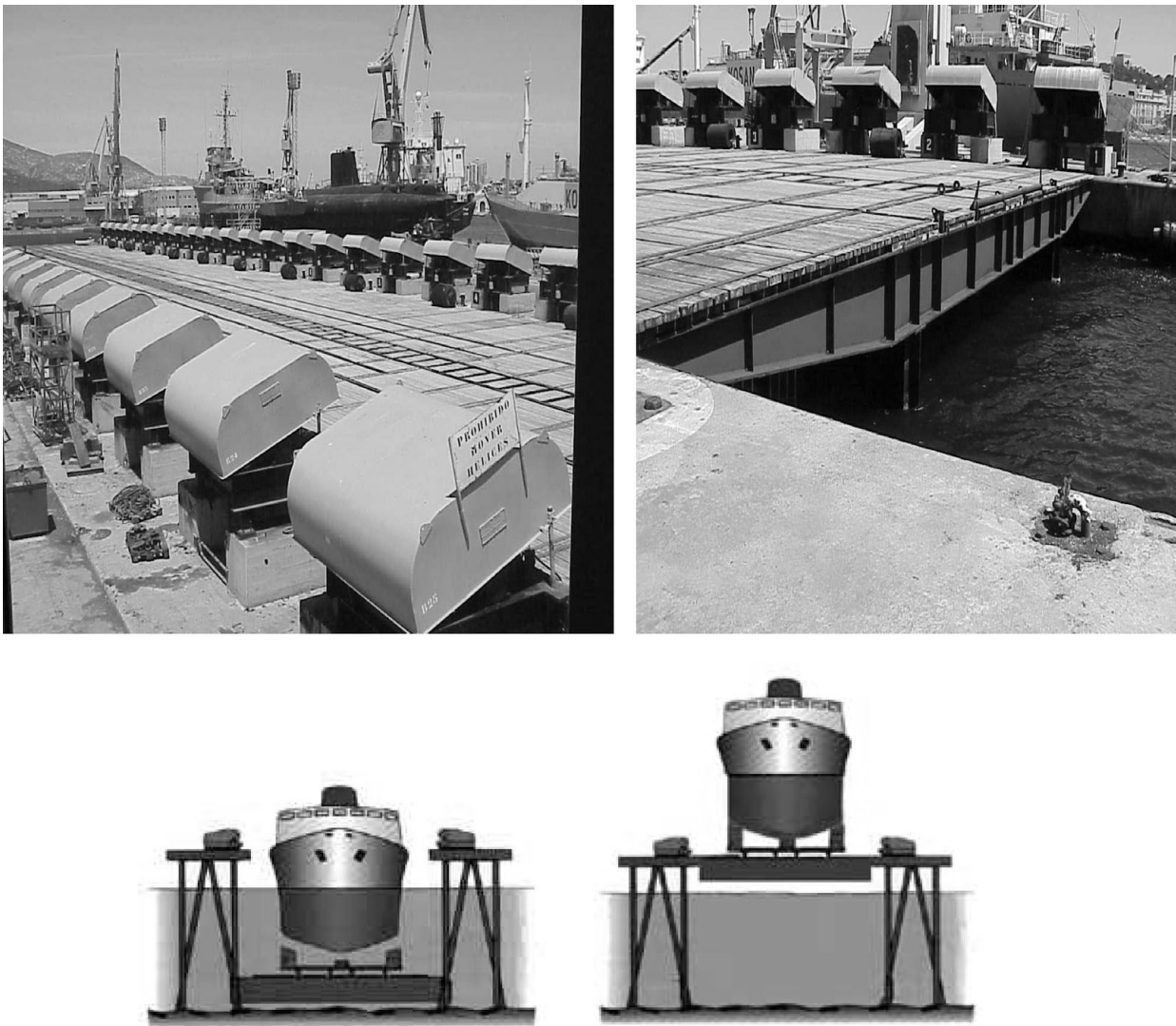


Fig. 3. Synchrolift: system for lifting boats and ships out of the water for maintenance work or repair (Length: 150 m, Width: 25 m, and Height: 15 m).

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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01. Vertical structure.
02. Trusswork basket.
03. Hoist lifting system.
04. Steel cables.
05. Counterweight.
06. Folding trusswork arm.
07. Folding base plane.
08. Connection structure.
09. Secondary system (XYZ table).
10. Wheel with gearmotor.
11. Rails.

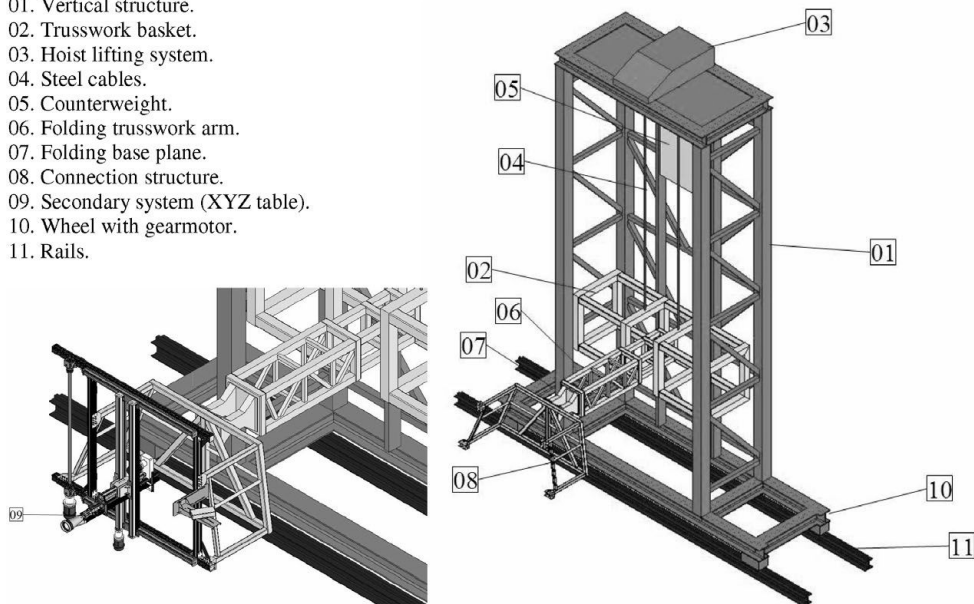


Fig. 4. Robotized tower with articulated arm for Synchronlift system.

297 The vehicle consists of two 1.57 kW AC servomotors  
 298 (Fig. 7-01) of 3000 rpm, 5 Nm, each with braking control,  
 299 and planetary differential relationship  $i=10$ , mounted  
 300 lineally in an opposed way, which drive on two gear  
 301 aluminium wheels (Fig. 7-02) covered with double toothed  
 302 polyurethane belts (Fig. 7-03). The vehicle has a mounting  
 303 bracket structure (Fig. 7-04) which is, in the central section,  
 304 expandable and adaptable to the different sizes of the blasting  
 305 hood (Fig. 7-05). This hood has a grit entry (Fig. 7-06) and  
 306 a suction confinement inlet (Fig. 7-07). As it has already  
 307 been mentioned, the vehicle adheres magnetically to the hull  
 308 of the ship by means of 16 permanent square magnets of  
 309 neodymium (Fig. 7-08) of  $55 \times 55 \times 15$  mm, which are  
 310 enclosed within stainless steel boxes. These are distributed  
 311 homogeneously throughout the whole vehicle, and generate  
 312 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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- 01. Aluminium profile framework.
- 02. Mechanical cylinder without rod. X axis.
- 03. Drive axle.
- 04. Mechanical cylinder without rod. Y axis
- 05. Mechanical cylinder without rod. Z axis.
- 06. Blasting hood.
- 07. Grit inlet.
- 08. Suction outlet.
- 09. Shock-absorbing structure.
- 10. Watertight case for computer vision system.
- 11. Mounting bracket.

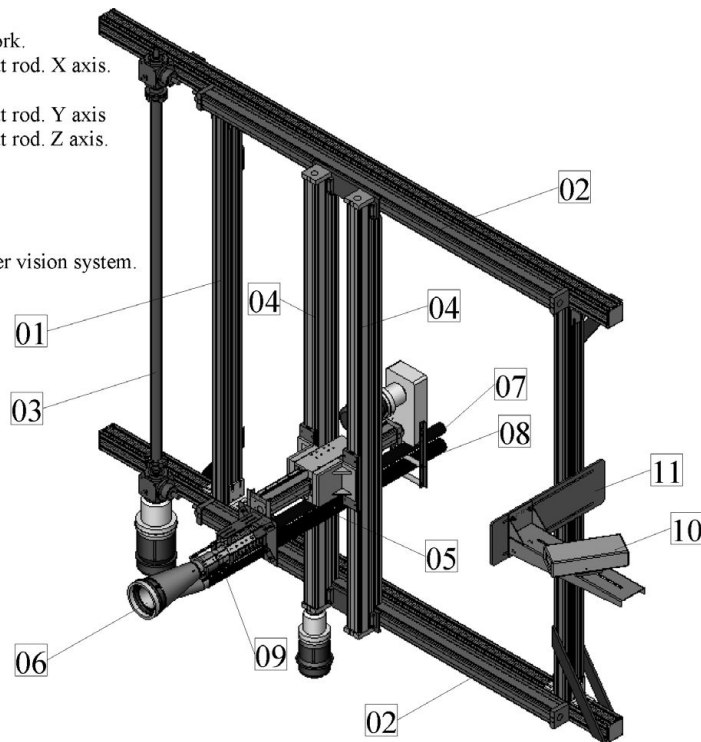


Fig. 5. Details of the robotized tower with XYZ table.

not an industrial vehicle yet, like Ultrastrip System,<sup>7</sup> 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.<sup>13</sup>

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.<sup>15</sup> Their development is



- 01. Vertical structure.
- 02. Trusswork basket.
- 03. Hoist lift system.
- 04. Steel cables.
- 05. Counterweight.
- 06. Secondary system (XYZ table).
- 07. Wheel with gearmotor.
- 08. Rails.

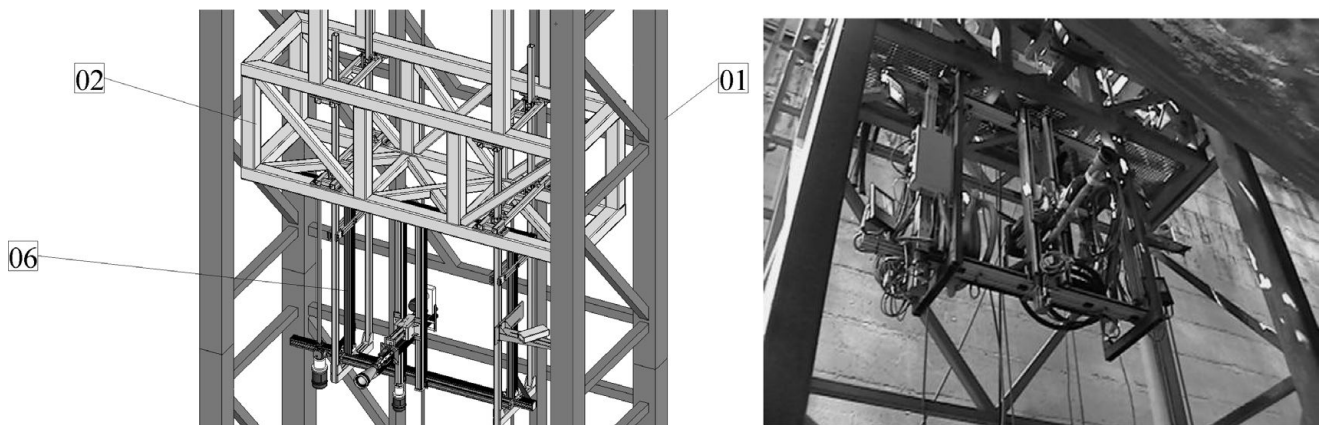
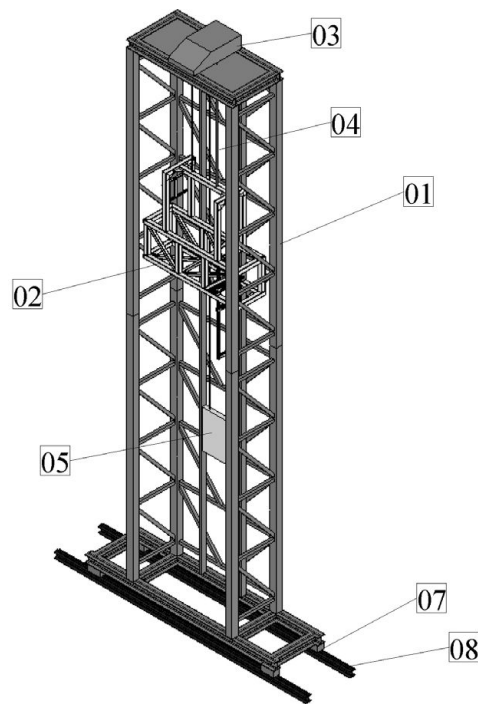


Fig. 6. Dry dock tower with secondary system mounted (XYZ table).

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

403 • **The inferior level corresponds to each one of the local**  
 404 **control units of the service robots.** Each control unit has  
 405 its own architecture adapted to its functionality, from pure  
 406 teleoperation to very high levels of autonomy. This aspect  
 407 represented a new technological challenge, in the sense of  
 408 being able to reuse complete functional blocks in robots  
 409 with very different control architectures. This led us to  
 410 develop an architectural framework to design control units

(ACROSET),<sup>17</sup> in which a fundamental aspect is the use  
 of advanced concepts of software engineering, especially  
 the component based development paradigm.<sup>18</sup>

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



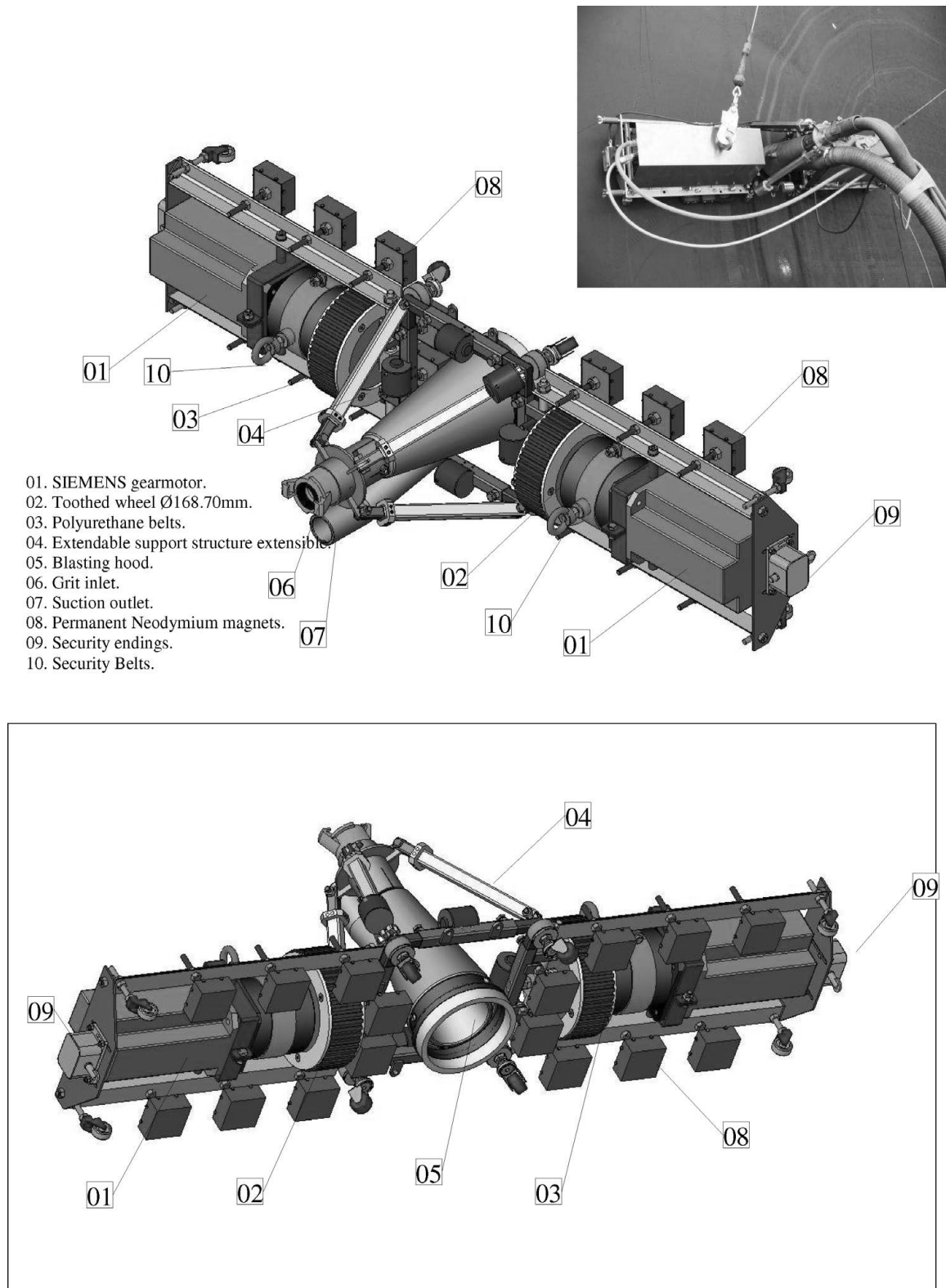


Fig. 7. Climbing Vehicle, top and bottom views.

429 will carry several cleaning tables, and which will thus need a  
 430 certain degree of cooperation among them. A higher degree  
 431 of cooperation will also be needed when working with several  
 432 towers or climbing vehicles, but this depends on budget of  
 433 the shipyard and its needs. In any case, this architecture is  
 434 flexible enough to accommodate these kinds of requirements.  
 435 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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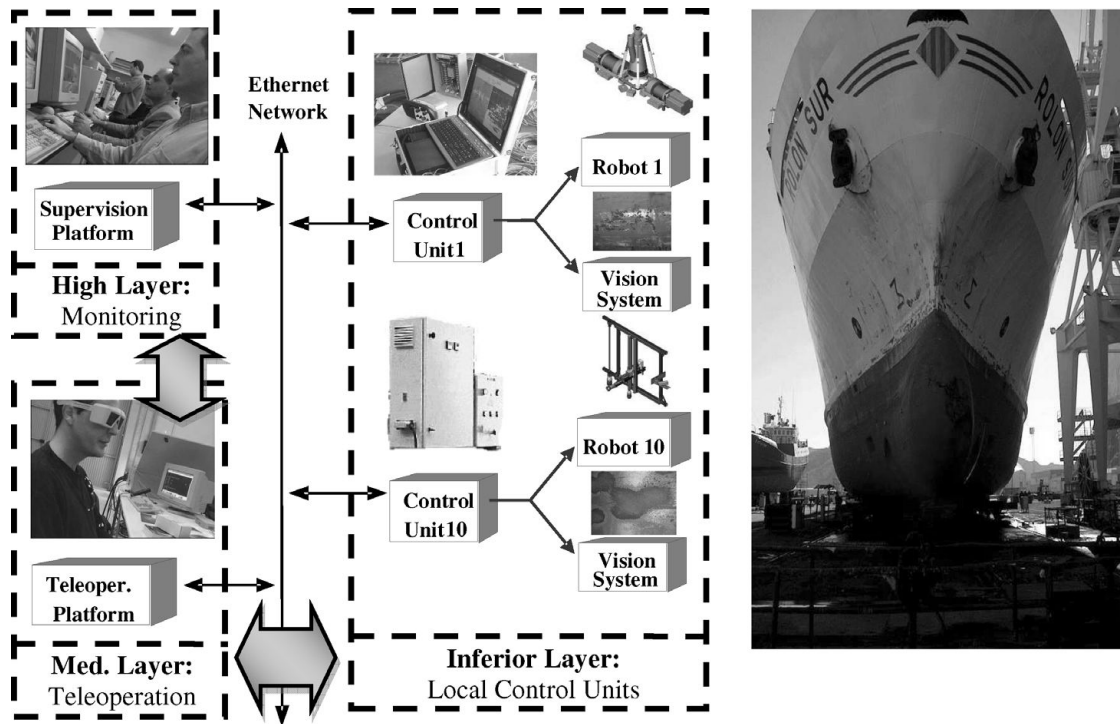


Fig. 8. Global outline of the EFTCoR system. The figure depicts the three layers the global architecture has been divided into, together with the data and command flow among them (big grey filled arrows). It is also remarkable that the whole system is linked by means of an Ethernet network.

443 diverse software components (computer vision system for  
 444 the control unit under consideration, relations to the higher  
 445 levels, synchronism with external systems such as that of  
 446 the recycling, sensorial systems, local control of axis and  
 447 tools, etc.). Our concern is not only with what is done but  
 448 also with how it is done. Hence our interest in applying  
 449 state-of-the-art software engineering paradigms (software  
 450 architectures,<sup>19</sup> component oriented programming<sup>20</sup> and model  
 451 driven engineering.<sup>21</sup>)

## 452 6. Evaluation of the Benefits

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

457 In order to evaluate the benefits of the EFTCoR robots,  
 458 it is necessary to bear in mind the type of ship used in the  
 459 tests, and the type of installation where they were carried  
 460 out. Table III details the most important characteristics of  
 461 the ships in the shipyards where our robots were evaluated.  
 462 As can be seen, the sample is sufficiently representative that  
 463 the results obtained can be generalized to any other type of  
 464 shipyard. Table IV summarizes the results achieved with the  
 465 family of robots EFTCoR in the two reference shipyards,  
 466 and the comparison of these results with the parameters  
 467 obtained using the usual manual procedure. The parameters  
 468 that have been recorded are those related to the hourly and  
 469 total efficiency (included downtimes), as well as the costs.  
 470 It is possible to appreciate important differences between  
 471 each shipyard due to the different working environments, as  
 472 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<sup>2</sup>/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<sup>®</sup>) 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.

## 492 7. Conclusions

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

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

Table III. Characteristics of the ships according to shipyard.

Shipyard	DWT <sup>a</sup> (Ton)	Beam (m)	Depth <sup>b</sup> (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

<sup>a</sup>Deadweight Tonnage.

<sup>b</sup>(from the keel to the flotation line).

Table IV. Comparison of manual – automatic results.

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

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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