Development of a Climbing Robot for Grit Blasting Operations in Shipyards

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***Abstract*— This paper deals with the design and construction of a climbing robot for performing grit blasting operations in shipyards. The robot is based on a double sliding platform that uses permanent magnets for attachment. It is lightweight and compact and can move up and along the shipside with any inclination while grit blasting the surface to pre-specified surface quality levels. It can also rotate to compensate for hull curvature and to avoid obstacles while performing its task. The blasting operation is modulated by a vision based quality control system that is used by the mission control system to adapt the blasting parameters in order to attain the desired quality levels while maximizing the surface area the robot strips per unit time.**

I. Introduction

One of the main surface preparation operations in shipyards is that of surface coating removal. This process may take place when a ship is built and just before painting it, so that the surfaces conform to a pre-established standard, or as a part of a periodic maintenance process whereby paint is removed and the ship repainted. There are different technologies for cleaning and stripping ship surfaces, but the most relevant are abrasive blasting and ultrahigh pressure water-jetting. The former is the traditional technique and has been around for more than a century. It consists in blasting the hull with small particles of sand or metals (sand blasting or grit blasting) within a high pressure fluid, generally air or water. The most commonly used systems in shipyards are manually operated hoses that project grit at high speeds by injecting pressurized air at a pressure of around 8 Kg/cm^2. It is a very effective technique in terms of the final surface results; however, it presents many drawbacks when considering the environmental implications of the process and the hazards for the human operators performing the task.

In the last decade or so new environmental regulations have led to an increasing use of ultra high pressure water jetting as an alternative to abrasive blasting in certain operations. These techniques, although much more environmentally friendly, do not achieve the performance levels of sand or grit blasting regarding steel surface preparation for optimal paint adherence. In addition they are generally more expensive and it takes longer to prepare the same surface.

In this line we have been commissioned by the Navantia Shipyards in Spain to explore the possibilities of producing a grit blasting system that would compete in terms of environmental friendliness with current water blasting systems and that would not be hazardous for human operators. Thus, we have designed a system that is based on two main blocks: A closed circuit grit blasting head that recovers the grit and the stripping residues through a vacuum system and which is being developed jointly with the research department in Navantia and a semi-autonomous climbing robotic system that is able to perform the whole surface preparation operation with very little human assistance. The objective of this paper is the presentation of this second block.

A. Related work

In the ship construction area the introduction of robotics has been slow due to the special characteristics of this industry, such as a very dynamic and unstructured work environment and the fact that operations are not carried out in a controlled production line but rather on the constructed object itself. Experiences in the introduction of robots can be found since the end of the eighties [1], but they have not really taken hold in the industry until more recently and only for particular operations such as inspection, welding or hull cleaning. A review of these systems may be found in [2] and recent experiences in this line are those of Fei and Wan [3] who developed a climbing inspection robot with four magnetic wheels or Lee et al. [4] who have designed a rail runner mechanism that carries a robotized arm for welding in double hull structures.

In the particular subfield we are interested in, some work has been carried out in the last decade in the development of robots for hull stripping and surface preparation. Most of it has considered water jetting as the main stripping technique. The most important example is the Ultrastrip series of Robots developed at the Carnegie Mellon University Robotics

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Institute [5] and later commercialized by Ultrastrip Systems. These robots are based on air gap magnets for fixation and wheels for motion. The 200 plus Kg robots were remote controlled and they carried around a water jet head within an enclosure for vacuuming the residue. This approach was quite successful, but, as indicated above, water jetting does not achieve the same level or steel surface preparation as grit blasting systems and thus is not appropriate for all cases.

Ortiz and his collaborators [6] have tried to automate the grit blasting operation by using a remote controlled robot arm with a blasting head positioned on an elevation platform. The externally controlled platform is moved along the length of the ship and raises the arm to the positions where it must operate. These authors have shown that high levels of surface quality can be achieved this way, but the system they implement is quite cumbersome.

In this work we have tried to produce a smaller, lighter and more autonomous system that could achieve the same or even better surface quality results. To this end we have designed, constructed and tested an 80 kg sliding type pneumatically actuated structure that can walk on the hull carrying the blasting head and cleaning a 80 cm wide path as it moves. The double sliding structure provides enough degrees of freedom to turn as desired and is fixed directly to the hull by means of NdFeB permanent magnets. These are demagnetized as needed by means of internal demagnetizing coils. The control of the structure is modulated by a quality verification subsystem that using image based texture processing techniques decides if the goal surface quality has been achieved or if it is necessary to slow down or speed up the continuously blasting head or even redo a blasting pass and at what speed to provide an homogeneous quality level.

The following sections are devoted to the description of the mechanical system, the control structure, the quality verification system and some examples of its real operation.

II. Design of the Robot

The robot platform is in charge of transporting the grit blasting and quality verification equipment. Its description has been divided into four subsections that reflect the different aspects of the design.

A. Mechanical Design

The system (Fig. 1) is based on two modules that can move relative to each other and which are endowed with independent leg based fixation and support systems. The relative motion of the modules allows the robot to move. The details of the kinematics are shown in Fig. 2. All of the motion related actuators are pneumatic as they are much lighter than electrical actuators and weight was a critical factor in the design. In addition, because of the compressibility of air, movement driven by pneumatic actuators is passively compliant facilitating the absorption of vibrations or small irregularities and leading to safer operation.

The lower module uses a linear actuator (S3) in charge of dealing with horizontal and robot advance movements. In addition it has a linear guide (S4). It is on these two elements where the coupling of the lower and top module takes place. This coupling is achieved by two non actuated joints (R1 and R2), which together with the linear guide (S4) permits the rotation of the modules relative to each other. It has two legs at each end which are actuated through linear actuators (T5-T8) coupled to magnets through ball and socket joints (BS5-BS8). This way, the magnets can adapt to small angle deviations of the hull surface, increasing their grip.

This module carries both the vision and quality control subsystem and the grit blasting head. The quality control subsystem consists of two camera boxes with intelligent cameras and illumination elements that carry out vision related alignment and blast strip length control tasks when located before the advancing blasting head or surface quality verification when located behind it. They are positioned before and behind the blasting head and switch functions depending on the direction of motion of the head. In fact, the cameras and the blasting head are moved together by means of a linear actuator (S5).

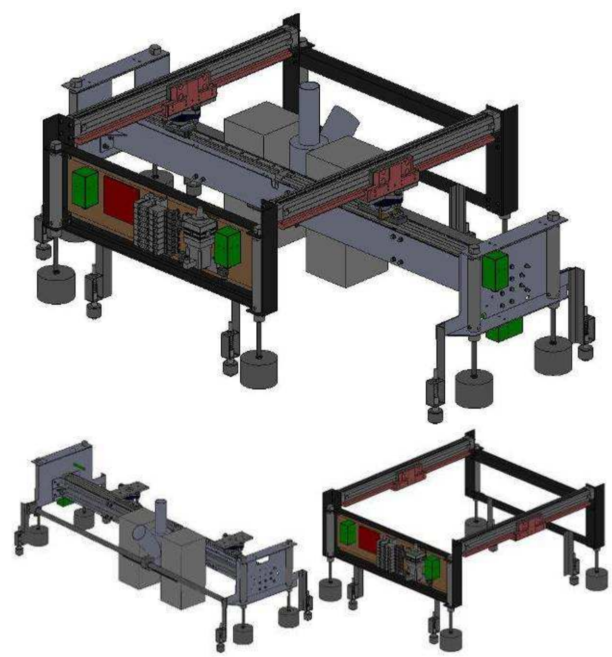

Fig. 1. The complete robot (top) and the lower and top modules (bottom).

The top module has two parallel linear actuators (S1 and S2) that are connected through beams that conform a rigid rectangular structure. These actuators are in charge of the vertical motion of the robot on the hull when actuated together as well as of performing relative rotations between the modules when actuated independently. In these actuators, a pneumatic breaking system in the slider prevents the vertical displacement of one module with respect to the other. The top module also has four actuated legs, located at the vertices of the rectangle, and carries the robot control system.

Before moving, each module demagnetizes its magnets and retracts its legs. In order to prevent uncontrolled moments from appearing at the couplings of the modules, there is a mechanical support element beside each magnet consisting of a leg with a spherical wheel.

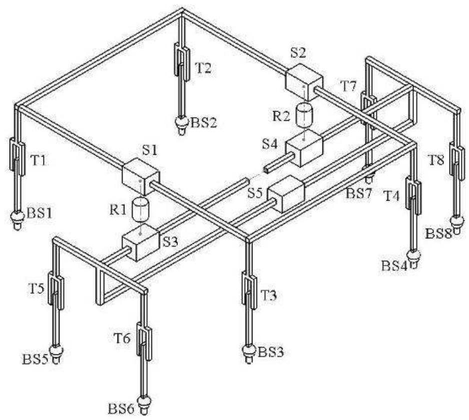

Fig. 2. Robot kinetics diagram.

B. Motion of the Robot

The operation of grit blasting the hull is carried out as follows. The robot is placed on the hull. The blasting compressor is turned on and the head starts blasting away (it is not turned off until the end of the operation). The blasting head is moved by the robot horizontally for around 80 cms until it reaches the end of the robot working area. The bottom module is then moved up appropriately and the blasting head starts to move horizontally in the opposite direction until it reaches the end of the working area.

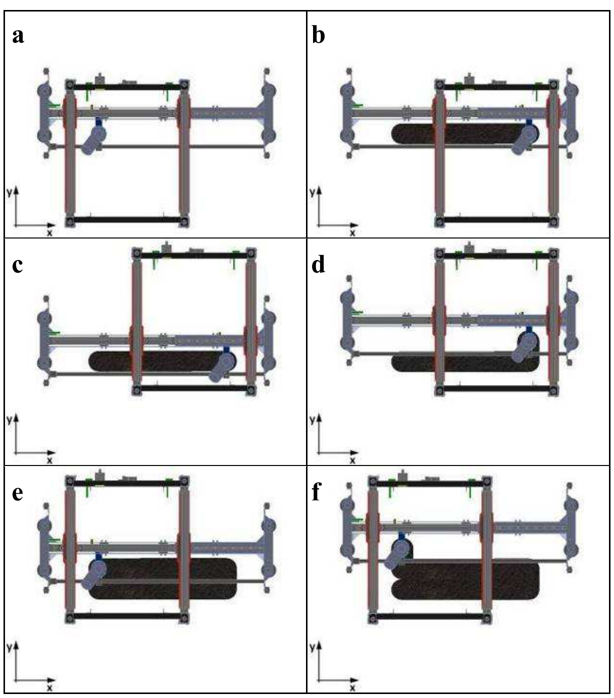

Fig. 3.Blasting sequence (left to right, top to bottom).

TABLE I
Robot Characteristics

	Size	Weight
Top Module	1000x850x500 (mm)	45 (kg)
Lower Module	1580x530x500 (mm)	35 (kg)
Stroke Length (mm)	Head Actuator (S5)	1200
	Actuators S1 and S2	600
	Actuator S3	600
Velocity (cm/s)	Blasting Head (S5)	12-40
	Actuators S1 and S2	20
	Actuator S3	20

Consequently, the head will blast horizontal strips stacked one on top of the other until the bottom module reaches the top end of its possible motion under the top module. At this point the bottom module is fixed to the hull and the top module is displaced up until the bottom module is at its bottom and the operation resumes as before. When the top of the area that must be grit blasted on the ship hull is reached, the bottom module is moved completely to one side of the top module, fixed to the hull, and the top module displaced over it until a new vertical strip can be blasted, and the operation starts again, this time descending down the hull. The sequence of motions performed by the different elements of the robot in order to blast a working area is shown in Fig. 3. Figure 4 displays the trace of one of these blasting operations.

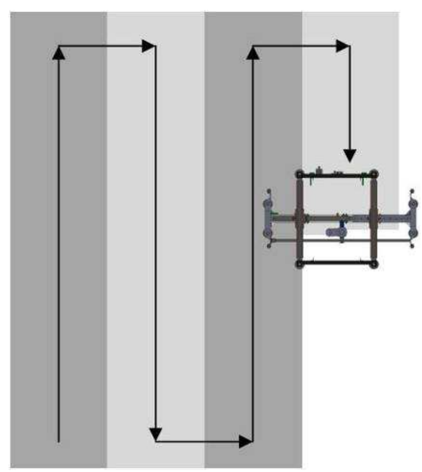

Fig. 4. Trace of a blasting operation

C. Fixation System

As the robot had to move over a ferromagnetic surface, we have chosen a permanent magnet based fixation system. They are safer in case of system malfunctions than other options such as electromagnets or vacuum based system.

The selected magnetic fixation system consists of NdFeB magnet shells with electromagnet coils inside them that permit generating magnetic fields opposite to those of the permanent magnets, thus allowing for the system to produce no magnetic field and thus become unfixed. In addition to being a very simple and elegant way of achieving the fix-unfix actuation there was one more reason why this type of strategy was chosen and it has to do with the operation of the robot. Grit blasting generates lots of ferromagnetic metallic dust and particles and they tend to become attached to the magnets. The demagnetizing action used as part of the robot movement operation, allows for the elimination of stray particles from the magnets in a cyclic manner. Otherwise they would accumulate and render the magnets and the system unusable. A further advantage of this implementation is that the electromagnets within the permanent magnet shell can also be polarized to produce a magnetic field that is aligned with that of the permanent magnets, thus increasing the grip when necessary.

D. Robot Control System

The operation control system is divided into two parts: The robot control system and the mission control system. The robot control system is made up of a microcontroller that receives high level mission commands from the mission control base station, controls the different robot elements and regulates communications with the base station.

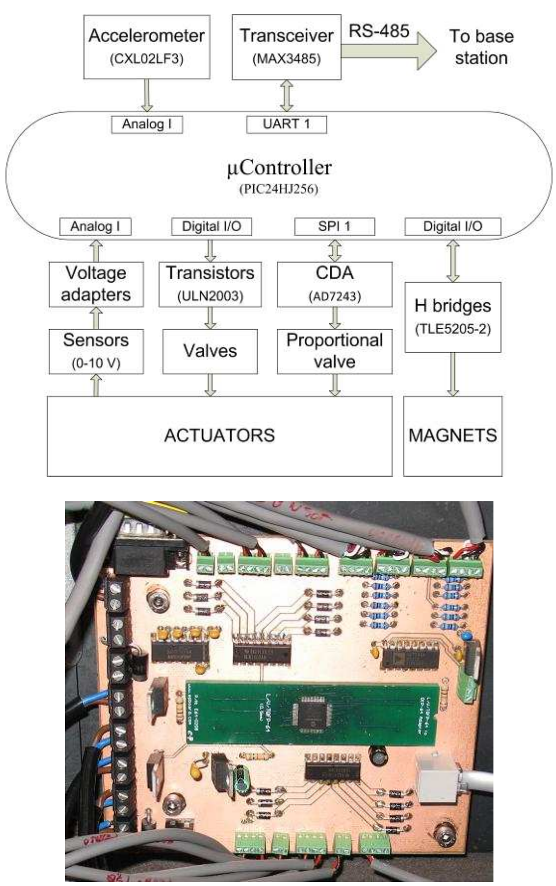

Fig. 5. Block diagram of the control electronics and picture of the main control board developed.

Fig. 5 displays a block diagram of the robot control system and a picture of the main board. The commands are received through an RS-485 interface. They are interpreted by the microcontroller who sends the necessary control signals. The valves (inductive loads) are activated by means of ULN2003 transistor arrays. The proportional valve that controls the blasting speed is controlled by means of an AD724 digital to analog converter and the electromagnets through H bridges.

The sensors on the robot are, on one hand, linear sensors that measure the position of the four double effect cylinders and, on the other, a three axis accelerometer that provides information on position and inclination of the robot.

III. Mission Control

The mission control element in the base station is responsible for establishing the path to follow and decompose it into commands for the robot. It must also consider the quality of the grit blasting operation as obtained from the information provided by the cameras on the robot and control the position of the robot to modulate the blasting operation.

Mission control for the system may be carried out in a manual, semi-automatic or fully automatic mode. In the manual mode, the commands are sent to the robot by introducing the final position of each actuator in the base station interface. The semi-automatic mode allows for the selection of the direction of motion of the robot. Once it has been selected the commands for the actuators of the robot are generated automatically. The robot moves in that direction until another command is provided. Finally, in the automatic mode, a path is automatically generated for cleaning the area indicated by the user and the commands for the actuators as well as the possible adaptations in order to follow this path as a function of sensing are automatically sent to the robot.

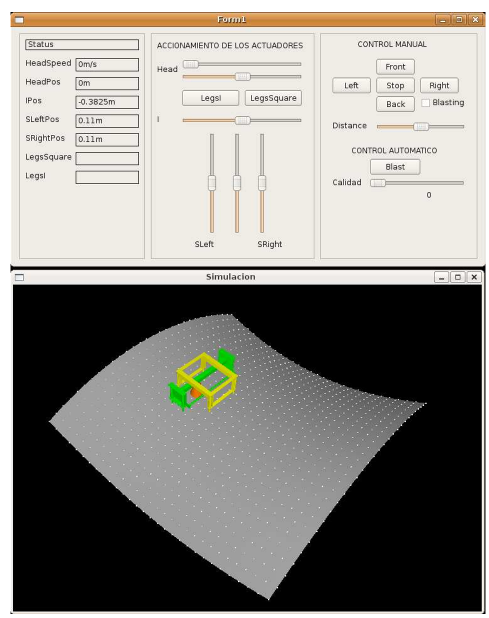

Fig. 6. Mission control GUI and robot simulator.

Mission control is also responsible for deciding, based on the information provided by the surface quality control subsystem, whether it is necessary to redo some part of the blasted area or to modify the blasting and motion speed in order to improve the results when the minimum quality desired for the operation has not been achieved. It is important to note here that a compromise between surface quality and system speed (square meters that are cleaned per unit of time) is necessary. The robot must achieve the minimum surface quality required for that particular operation at the highest possible speed through the regulation of the blasting head speed.

In terms of user interface in the base station, we have developed a visual interface that allows for the control of all the parameters and operational variables and displays either an image of the operation of the robot or a simulation of the run (Fig. 6). The simulator permits planning missions for the robot and determining optimal paths as well as introducing forbidden areas and other information.

The position of the robot is obtained through a cricket module based system [7]. These motes are located on the robot and around the area of operations. To complement the cricket data, the mission control system uses odometric information and the data coming from the accelerometer in order to improve accuracy. We are now in the process of developing an additional vision based module, using the cameras that are already on the robot, which would allow us to detect welding seams and use them to establish known reference points, thus increasing the accuracy even further.

IV. Quality Control

The robot performs the grit blasting operation in an unsupervised manner. Consequently, it is necessary introduce a system for verifying that the desired quality levels are met and, when they are not, inform the mission control subsystem so that it can take measures to improve the situation.

For the first operations only three quality levels were considered, as they were required by the shipyard. They are SA1 (little erosion, low granularity), SA2 (eroded surface, poor finishing) and SA2½ (eroded surface, good finishing). Fig. 7 displays these qualities and their FFTs.

To try to determine the quality levels, a trivial approach to texture processing could be applied. Basically, the higher frequency spectral signature in the power spectrum should provide an indication of granularity. However, this method does not lead to a robust enough classification due to irregularities in the images. In order to improve the decision, a Laws filter based processing stage [8] was implemented. Each sub-window is convolved with different 2-D Laws filters to obtain filtered images. Then, the sum of the squares or absolute values of the filtered images are used to construct a feature vector (*n* element vector for each sub-window). This method has been shown to exhibit a performance that is comparable to the Karhunen-Loève Transform based methods and it improves on Gabor filters [9]. Fig. 8 compares the descriptors for a test image with SA2 quality to the different reference descriptors. Note how close they are to those of the SA2 reference.

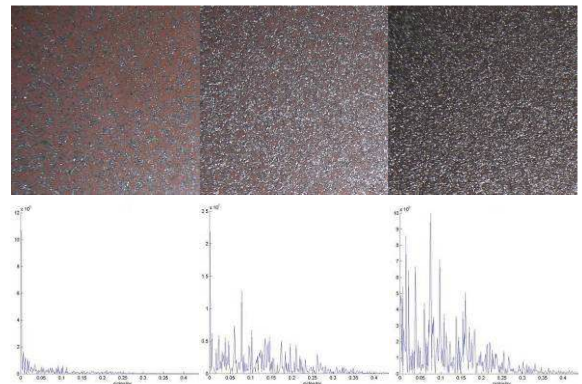

Fig. 7. Pictures of areas with different qualities and their FFTs (from left to right, SA1, SA2 and SA2½).

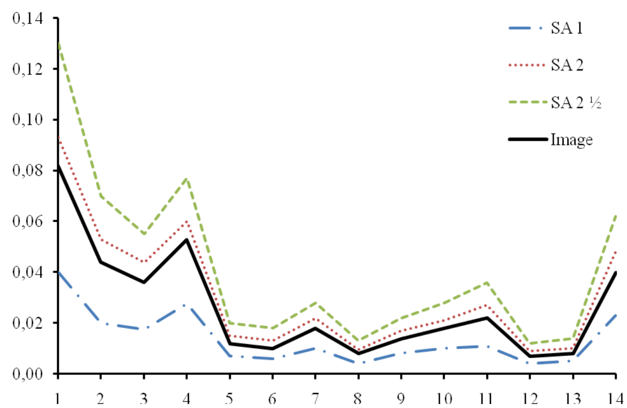

Fig. 8. Comparison of the descriptors (x axis indicates descriptor, y axis value) for an image with SA2 quality (black line, second from bottom) to the different reference descriptors. Note how close it is to the SA2 reference.

The acquisition of the images for quality verification is carried out by means of two intelligent cameras contained by two boxes on each side of the blasting head and which move together with it. Each box contains the camera; the LED based lighting system and the corresponding control circuits. Thus, when the head moves, one of the cameras (the one behind the head) can analyze the area that has been grit blasted determining the surface quality and the other one can be used for the detection of areas that have already been blasted in order to stop the blasting head or any other feature necessary for the control of the system such as welding seams, obstacles not to be blasted (portholes), etc.

The intelligent cameras are connected to the base station through an Ethernet link and contain a video processor where the Laws algorithm has been implemented. The cameras themselves perform the image processing tasks and send the results to the base station.

V. Some Tests

The robot was tested under different circumstances. In figure 9 we display one of the tests on a test environment that was designed for the robot to operate in the most unfavorable circumstances: a 10 mm steel ship hull plate painted with a shopprimer and with an orientation of 90 degrees with respect to the horizontal. This is the worst possible scenario because the robot must avoid sliding down the hull through the friction generated by the magnets (which produce a force that is mostly normal to the surface) and the hull surface. The friction coefficient is quite low making this friction force much lower than the one produced by the magnets. The figure shows a sequence of images displaying a 90º rotation of the robot, which is one of the most complicated maneuvers.

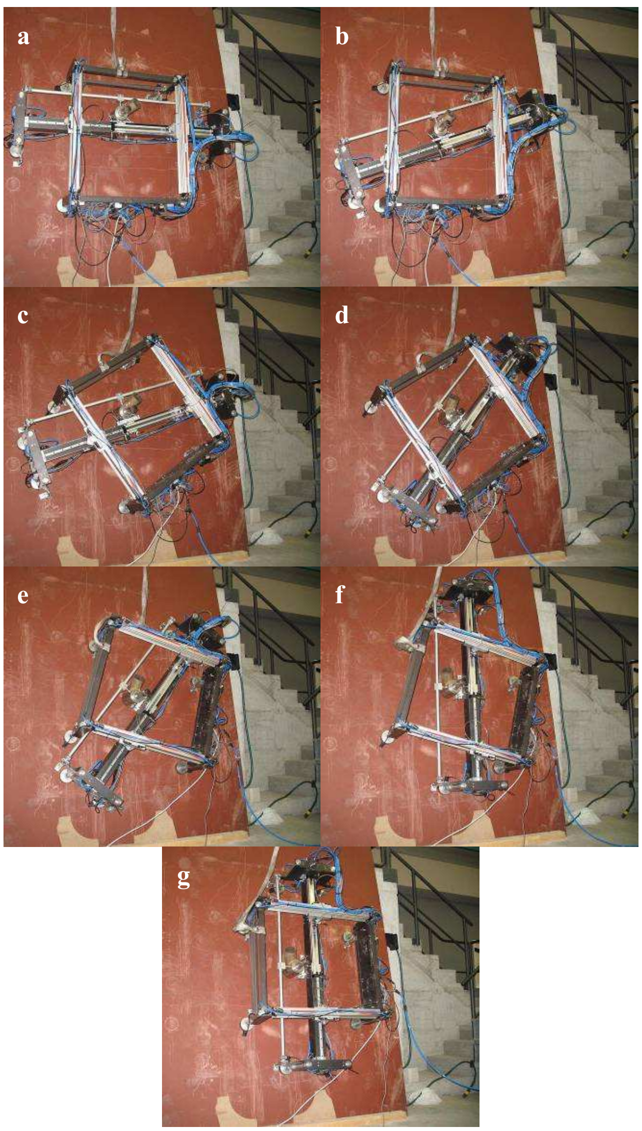

Fig. 9. Sequence of pictures showing a 90º robot rotation maneuver (~40 seconds). For the sake of clarity the quality control system boxes and the hoses to the blasting head were taken out.

VI. Conclusion

This paper describes a semi-autonomous robot for grit blasting operations that was developed with the aim of implementing a lightweight and easily deployable system that could automatically control the blasting head in order to achieve specified surface qualities for large areas as fast as possible while avoiding obstacles and areas that should not be blasted and compensating for hull curvature and irregularities. The robot is based on a pneumatically actuated double sliding mechanism which allows for displacements and rotations. It includes a quality verification subsystem that modulates its operation.

The system was constructed and tested under different circumstances providing very good results. We are now working in its introduction in real shipyard settings.

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References

[1] J. M. Kalogerakis. “Use of Robots in the Shipbuilding Industry”. The Naval architect .July/August, 1986.

[2] M.Armada, M.Prieto, T.Akinfiev, R.Fernández, P.González, & al., “On The Design And Development Of Climbing And Walking Robots For The Maritime Industries”. Journal of Maritime Research, Vol.II.No.1, 2005, pp.9-32

[3] Fei, Y., & Wan, X. Z. “Motion Analysis of a Modular Inspection Robot with Magnetic Wheels”. Proceedings of the 6th World Congress on Intelligent Control and Automation, 2006 , pp. 8187-8190.

[4] Lee, D., Lee, S., Ku, N., Lim, C., Lee, K.-Y., & Kim, T. K. (2008). “Development and Application of a Novel Rail Runner Mechanism for Double Hull Structures of Ships”. Proceedings of the IEEE International Conference on Robotics and Automation 2008, pp: 3985-3991.

[5] W.P. Ross, J. Bares, and C. Fromme. “A Semi-Autonomous Robot for Stripping Paint from Large Vessels”. The International Journal of Robotics Research, Vol. 22, No. 7 - 8, July, 2003, pp. 617 - 626

[6] Ortiz F, Iborra A, Marín F, Álvarez B, Fdez Meroño J.M., “GOYA: A teleoperated system for blasting applied to ships maintenance”, 3rd International Conference on Climbing and Walking Robots., CLAWAR'2000. Madrid,. October 2000.

[7] Nissanka B. Priyantha, Anit Chakraborty, Hari Balakrishnan, “The Cricket Location-Support system”, Proc. 6th ACM MOBICOM, Boston, MA, August 2000.

[8] Laws, K.I., “Textured Image Segmentation”, Report 940, Image Processing Institute, University of Southern California.

[9] Nezamoddin N. Kachouie, Javad Alirezaie. “OptimizedMultichannel Filter Bank with Flat Frequency Response for Texture Segmentation” EURASIP Journal on Applied Signal Processing 2005:12, pp. 1834–1844.