ISSN 1061-8309, Russian Journal of Nondestructive Testing, 2008, Vol. 44, No. 9, pp. 626–633. © Pleiades Publishing, Ltd., 2008.
Original Russian Text © T.S. Akinfiev, M.A. Armada, R. Fernandez, 2008, published in Defektoskopiya, 2008, Vol. 44, No. 9, pp. 53–63.

ACOUSTIC METHODS

Nondestructive Testing of the State of a Ship's Hull with an Underwater Robot

T. S. Akinfiev[a], M. A. Armada[a], R. Fernandez[b]
[a] Industrial Automation Institute, Spanish National Research Council (CSIC), Madrid, Spain
[b] Universidad CEU-San Pablo, Escuela Polit@ecnica Superior, Madrid, Spain
e-mail: teodor@iai.csic.es
e-mail: rofernandez@ceu.es
Received February 22, 2008

Abstract—The possibility of nondestructive testing of a ship's hull with the AURORA underwater robot is discussed. The robot performs underwater cleaning of a ship's hull with simultaneous contactless measuring of the thickness of the hull sheet with an ultrasonic detector; it tests the state of the protective coating and restores the shape of the underwater part of the hull.

DOI: 10.1134/S1061830908090064

Classification societies [1] (Lloyd's Register of Shipping, the American Bureau of Shipping, RINA, Germanischer Lloyd, Bureau Veritas, Det Norske Veritas, Russian Register, Polski Rejestr Statków) require inspection of the state of the outer steel hull of a ship no less than twice every five years, and the time between any two inspections should be no longer than three years [2, 3]. It is necessary to meet these demands to obtain a certificate for operating a ship. Before inspection of the state of a ship's hull, it is necessary to clean its underwater surface from marine fouling. Presently, these operations are performed manually in a dry dock; the cleaning time is about 24 h. After the cleaning is completed, an inspector visually checks the state of the hull and measures the hull thickness in different places (chosen by the inspector) with an ultrasonic probe. All this leads to substantial financial outlays due to the expense of work in the dry dock and high cost of out-of-service time (waiting for inspection, the ship's entrance into and launch from the dry dock). As a result, the owners of ships try to clean the body surface and inspect the state of the hull as seldom as possible.

An important aspect of this problem is the fact that, during cleaning of a ship performed manually with sandblasting or water-jet devices, the hull coating is partly damaged and particles containing heavy metals (zinc, tin, copper, lead) are thrown into the atmosphere. The mandatory 50-m safety zone around a ship being cleaned prohibits any other work in the dry dock during ship cleaning.

It should be noted that marine fouling not only impedes inspection of the surface state but also accelerates processes of coating fracture and corrosion, substantially increases fuel consumption, impedes control of the ship, etc.

In order to solve these problems in terms of a project supported by the European Community Commission, the AURORA underwater robot was developed, which can clean a ship's surface from marine fouling and simultaneously inspect the state of the hull of the ship afloat, without its entering the dry dock [4]. This robot ensures environmental safety because the cleaning waste, including small particles of paint, is collected in a special collector and then disposed of. Use of this robot makes it possible to substantially shorten the time between cleaning and ship surface inspection, to alleviate the negative effect of marine fouling (Fig. 1, solid line), and to increase the reliability of ship functioning due to earlier detection of hull flaws.

It cannot be unambiguously determined what time interval is preferable for cleaning and inspecting the state of a ship's hull; this depends significantly on many factors, in particular, on the type of paint covering the underwater surface of the ship's hull, the ratio between the standing and movement times, the water temperature, etc. When the ship is operated in warm water, cleaning may be required after six months. If cleaning is performed as required, the surface quality remains quite high (Fig. 1, solid line).

A scheme for mechanized underwater cleaning of underwater pipelines and other underwater structures from deposits is known [5]. However, the setups developed for these purposes are effective only for small areas to be cleaned. An attempt to use a special underwater means of transport equipped with mechanical brushes and controlled by a diver operator [6] for cleaning the underwater surface of a ship has also been

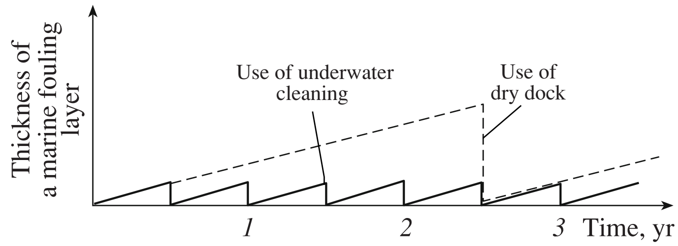

Fig. 1. Time dependence of thickness of a marine fouling layer.

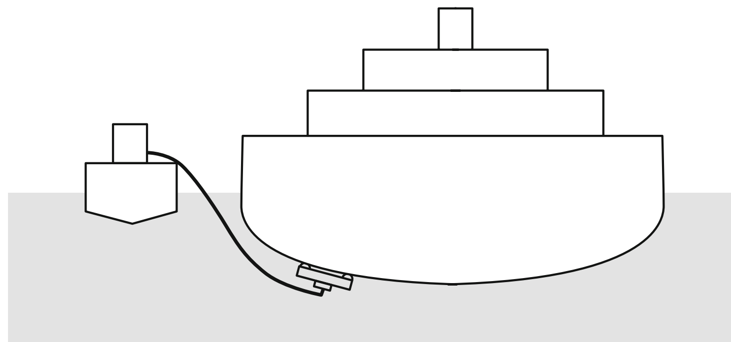

Fig. 2. Schematic view of interaction of the robot with a tested ship.

described. The main drawback of this design is that the operator should work under extreme conditions and cleaning of a ship with a surface of about 10000 m^2 takes many hours. Moreover, significant problems arise because marine fouling pollutes the water during cleaning, which sharply limits the possibility of visual estimation by an operator.

The AURORA underwater robot developed for the project can clean the underwater surface of a ship from marine fouling without its entering the dry dock, while the ship is afloat. The calculated time for cleaning is 24 h, and the minimum radius of curvature of the surface on which the robot can work is 2.5 m. Simultaneously with the cleaning, the robot tests the cleaned surface (the sheet thickness, the state of the protective coating). The basic operating regime is automated, but manual remote control in zones where there are protrusions of the cleaned surface, holes, etc., is allowed. An operator can control the automated cleaning and, if necessary, switch the system to manual control. The working place of the operator (the control board) is on a special boat or on the tested ship. The marine fouling removed from the treated surface is collected in a special vessel for subsequent disposal.

The setup for the underwater cleaning and the ship surface testing consists of two main parts: the underwater robot and the above-water part (Fig. 2), where the control board, the power supply, and the vessel for collecting the marine fouling are located. Structurally, the underwater robot is a pair of wheels with fixed equipment for the surface cleaning, including means for removal of products of cleaning and different sensors for testing the underwater surface of the ship's hull. In order to ensure stability of the robot during movement along a curved surface, a three-wheeled chassis is used, one wheel of which can be rotated by a special motor equipped with a sensor of the rotation angle. The equipment for cleaning the surface is a set of rotating brushes with working elements made of plastic to prevent damage to the protective coating during cleaning.

It was shown in [6] that, when these brushes work in water, a significant force is caused by the hydrodynamic effect and presses the brushes to the treated surface. On the one hand, this effect is harmful because it may cause excess pressure of the brushes on the treated surface, which causes fracture of the protective coating of the surface and significantly increases the load on the drive of the brushes. However, a special structure of the cleaning mechanism provides partial redistribution of this force on the robot wheels; therefore, a useful effect appears: a force that presses the robot to the cleaned surface. An additional pressing force is produced by permanent magnets fixed on the treated surface. This force provides reliable fixation of the robot on the treated surface and allows the robot to operate on surfaces at any angle to the horizontal line, including on the ship bottom.

The products of cleaning are removed from the working zone as with a vacuum cleaner. For this purpose, the working zone of cleaning is covered with a tight cup fixed on the robot and having a flexible fence in the bottom part of the cup. With a water pump, water is pumped out from the working zone together with the products of cleaning and through a flexible tube is transported into the collector of the cleaning products inside the robot, where they are separated from the water. Seawater penetrates into the cleaning zone through small gaps between the flexible fence and the cleaned surface. Thus, the water pressure in the working zone is somewhat lower than the external pressure. This leads to the creation of an additional force pressing the robot to the treated surface.

Two video cameras are fixed on the robot: one camera ensures the automated control mode (planning of the trajectory of the robot movement), and the other is for observing the working cleaning process and testing the state of the ship's hull, in particular, for transmitting an image of the cleaned surface, which allows an operator to control the cleaning quality and visually evaluate the quality of the state of the protective coating. An ultrasonic probe that allows estimation of the thickness of the metal sheet from which the ship hull's is formed is attached to the robot. The robot is equipped with a system of sensors that supply the control system with information about its movement direction, velocity, spatial position, etc.

The equipment on the control panel—the power setup, power supply sources, elements of the system of automated control, operator's working place, and box for collecting the removed marine fouling—ensures normal operation of the robot.

The control system of the robot (Fig. 3) consists of two parts, one of which is on the robot and the other of which is on the control panel. The control panel contains three computers, one of which is a server with the QNX 6.0 real-time operating system. This computer is on the robot and ensures control of the robot drives and the drives of the technological equipment. Two other client computers are on the control panel. One of them has the QNX 6.0 real-time operating system. The other is a client computer on which the operator works; it has the Windows XP operating system for the convenience of the operator (the Photon-QNX system is also possible, but the human–machine interface then deteriorates). Communication between all computers is provided by the TCP/IP protocol.

The QNX client computer serves for proximate analysis of video information from the video camera on the robot. On the basis of these results, the other client computer plans the robot trajectory during operation in the regime of automated control. In addition, this computer, on the basis of the information from the system of sensors, provides continuous modeling of the robot movement trajectory and can display 3D images of the robot position on the computer monitor, which should help an operator perform remote control. A color image of the treated surface of the ship's hull can be displayed on the operator's screen; numerical parameters characterizing the robot movement (linear and angular coordinates, movement velocity, etc.) are also displayed on the screen, as well as indicators characterizing the state of the technological equipment on the robot (Fig. 4).

Information from the video cameras is transmitted to special monitors on the control panel. All this helps the operator to control the operation process and, if necessary, to switch off the automated control mode and to switch to the manual control mode using a joystick or a mouse click on the corresponding button on the screen. The operator has the option of remotely controlling one video camera by rotating the cameras in two planes and changing the image size and can record on a videotape the information from the video cameras, and information on the sheet thickness of the ship's hull and on the coordinates of the robot in the ship's coordinate system.

In order to clean and test the entire underwater surface of the ship, the robot must scan along the treated surface. The presence of sensors of angular movement of all wheels and a rotation-angle sensor of the steering wheel provides automated control of the robot, in particular, during movement along the assigned trajectory, during rotation, etc. However, this control is efficient only on short parts of the trajectory that do not exceed several meters because of possible slips of the robot wheels. It should be noted that, to prevent wheel slip, a special algorithm for controlling the wheel motors was developed, which provided redistribution of the traction force on the wheels depending on the real pressing force on each wheel [7]. However, even a slight slip of the wheels and random roughnesses on the tested surface at great displacements cause significant inaccuracies in finding the robot position because of accumulated errors. In these conditions, it is necessary to constantly correct the information on the robot position with respect to the ship's surface contained in the control system.

Taking into account the above and depending on the problem to be solved, three different methods for controlling the robot or their combination can be applied:

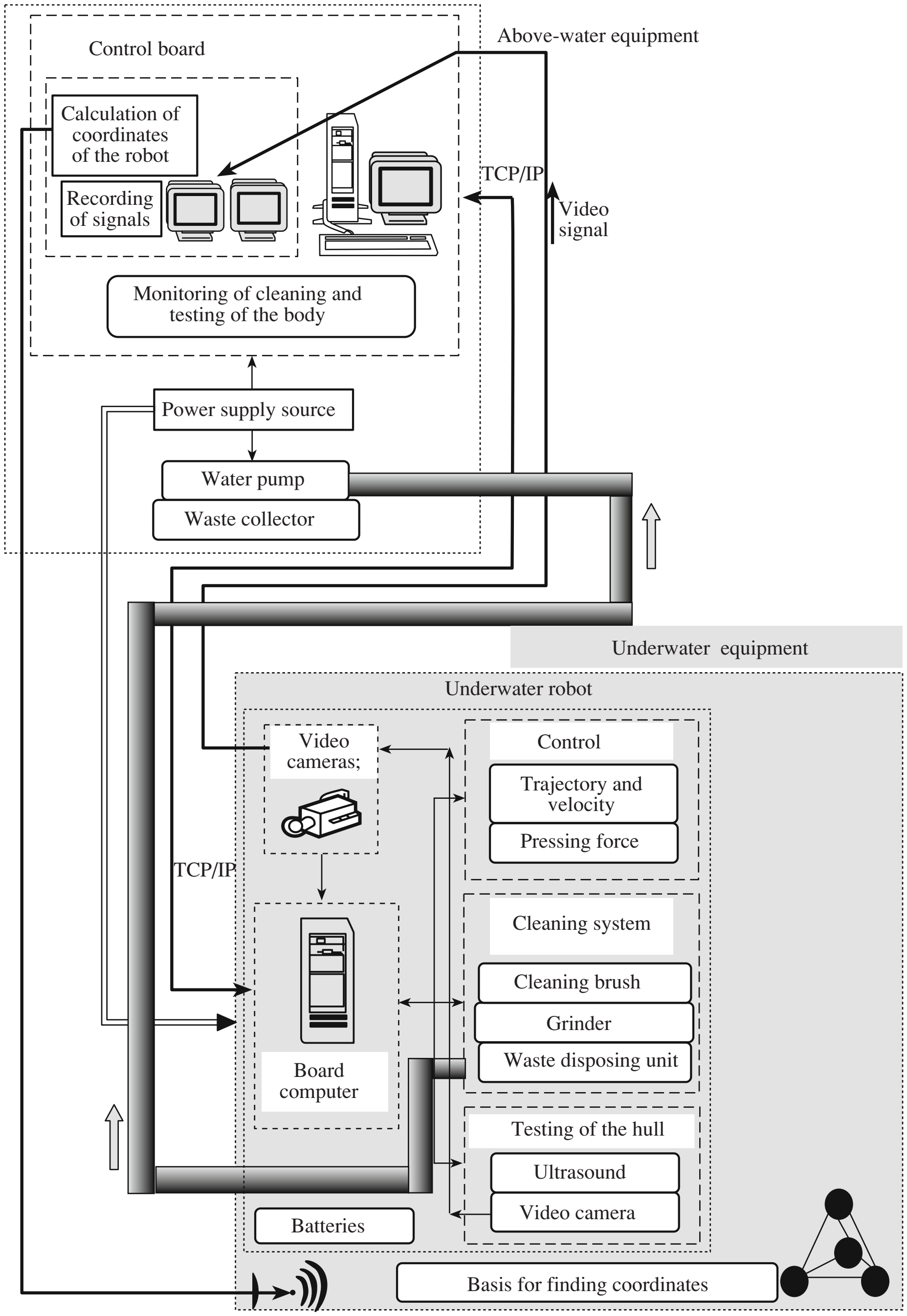

Fig. 3. Structure of above-water and underwater parts of the system.

(1) The manual control mode, in which, looking at the screen, an operator assigns the robot movements with a joystick.

(2) An automated control mode in which the robot movement direction is found on the basis of computer analysis of the video image. This method can be used when a small previously chosen area of the ship's hull is cleaned and tested. In this case, it is necessary to have information only on the relative position of the robot and the boundary separating the cleaned and tested area from the uncleaned area. A significant difference in the color between the cleaned underwater surface of the ship (as a rule, red-brown) and the surface with marine fouling (as a rule, green with gray inclusions) provides information on the boundary position on the basis of computer analysis of the video image. This makes it possible to correct on-line the robot posi-

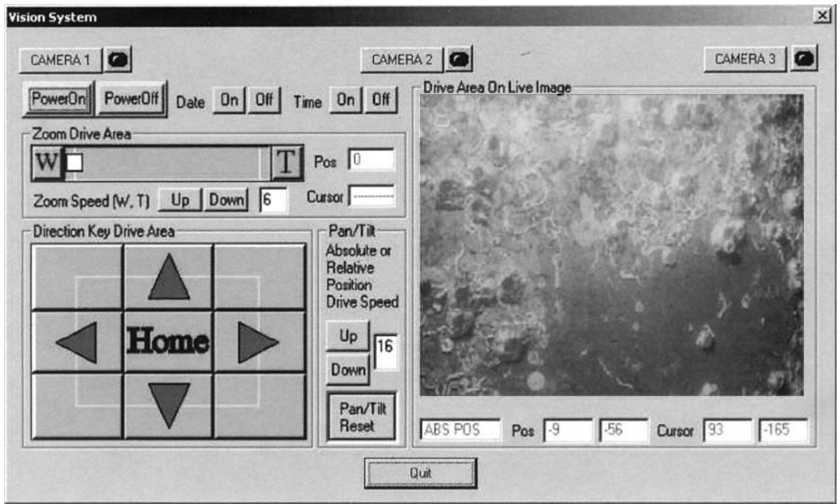

Fig. 4. A variant of the operator's computer display.

tion and ensure the robot movement along the boundary with displacements depending on the mutual position of the video camera and the cleaning mechanism.

(3) An automated control mode based on on-line calculation of the 3D coordinates of the robot in the ship's coordinate system. To implement this regime, an ultrasonic source is fixed on the robot and three ultrasonic sources are fixed on the ship's surface, thus making it possible to receive information on the robot position with respect to the ship. One of the drawbacks of this method is a weak resistance to noise, which is especially important when cleaning of the ship bottom is performed simultaneously with some repair operations, in particular, are accompanied by bumping, generating a wideband disturbance effect on ultrasonic probes. Information on the relative position of the robot with respect to the ship makes it possible to store in the computer memory the data on the cleaned and tested part of the ship. These data make it possible to clean and test the ship's hull state without the need to cease the normal operation of the ship. Thus, during loading of the ship in port, some part of its surface can be cleaned and tested, and the process may be continued at the next stop.

The thickness of the sheet of the ship's hull is measured in a continuous regime simultaneously with the process of cleaning the hull from marine fouling. The Krautkramer USM 25 ultrasonic device [8] fixed on the robot and connected to the board computer of the robot is used for the measurements (Fig. 5). This device is designed for the contact method of sheet thickness measurements, but experimental measurements have shown that, in the underwater position, it can work efficiently in the contactless regime after the corresponding tuning (Fig. 6).

As the intensity of the reflected signal received by the probe significantly depends on the distance between the probe and the studied surface, it is expedient to fix the probe on the robot so that the distance from the probe to the hull surface will be minimal. At the same time, it should be taken into account that the underwater surface of the ship is not plane and contains local protrusions (welded joints, different holes, etc.) and convex and concave surfaces. Taking into account that the minimum acceptable radius of curvature of these surfaces required for normal work of the robot is 2.5 m, it is found that, if the detector is rigidly fixed on the robot at a distance of 0.5 m from the robot wheel, the distance from the probe to the surface will change by 0.025 m during transition from a convex to a concave surface.

Fig. 5. Krautkramer ultrasonic probe.

In order to eliminate this drawback, a special mechanism for fixing the probe on the robot was developed (Fig. 7). The axle of this mechanism is fixed so that it can be rotated and moved with limited axial displacement on a cylindrical holder, which is tightly connected to the robot body. Between this cylinder and the axle of the mechanism, there is a spring; the axle contains a stopper that prevents the axle from falling out of the cylinder. On the other end of the axle, an additional passive wheel is mounted with displacement to provide movement along

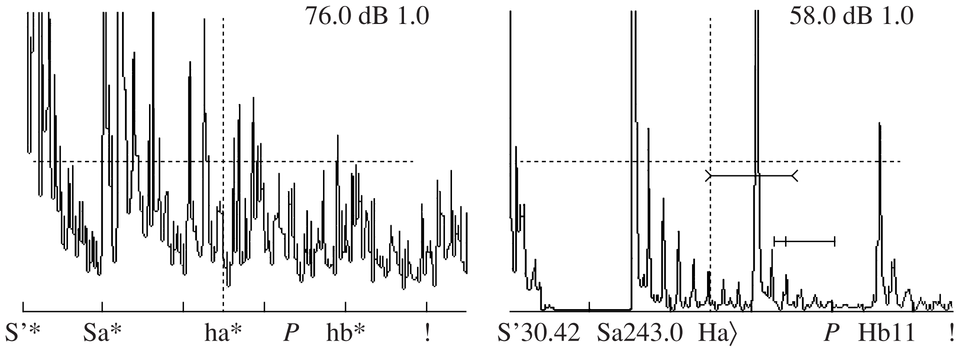

Fig. 6. Tuning of Krautkramer ultrasonic probe for underwater contactless measurements of the sheet of the ship's hull.

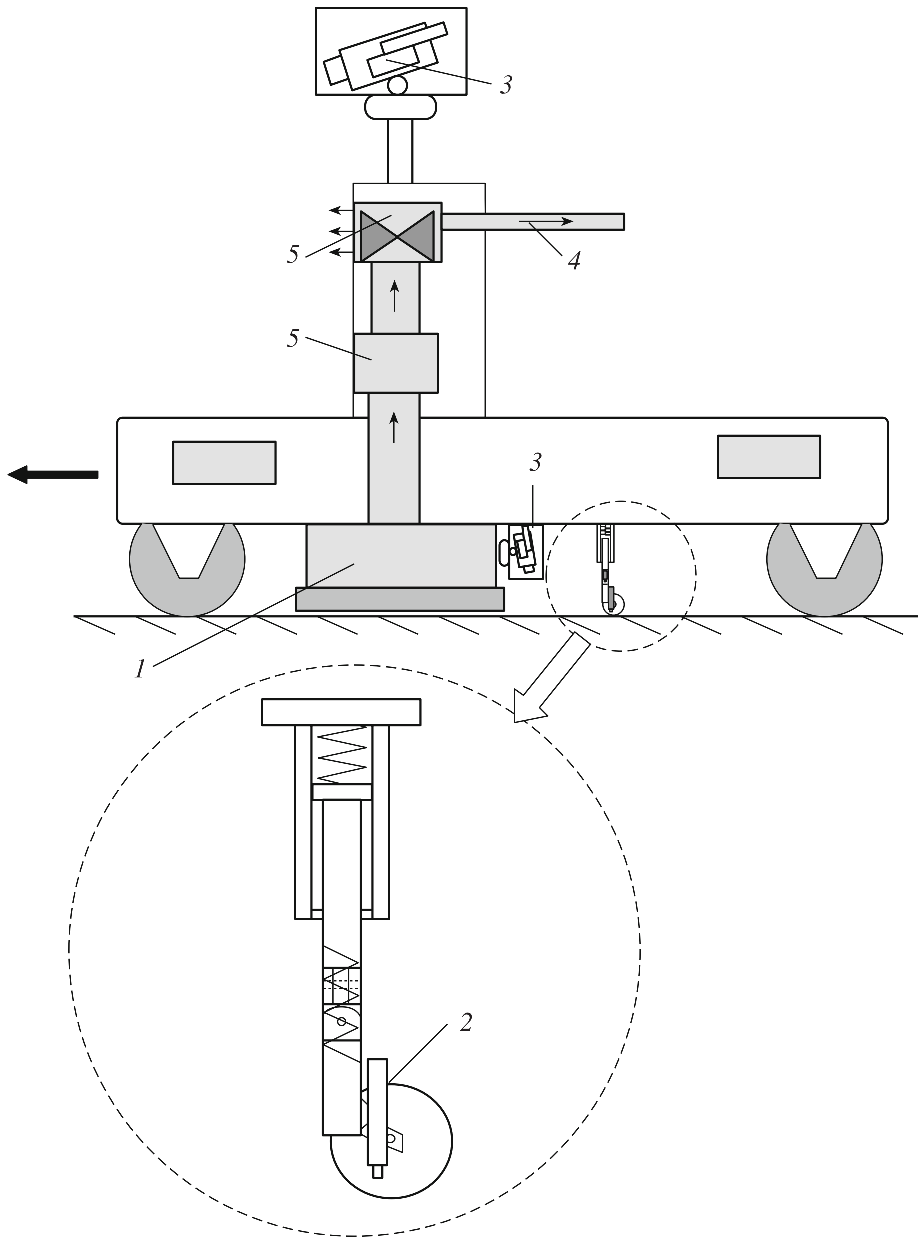

Fig. 7. Scheme of the underwater robot and device for testing the sheet thickness containing elements for its fixation: (*1*) cleaning brush with a fence; (*2*) ultrasonic probe; (*3*) rotating video camera; (*4*) tubes and cables connecting the robot with the above-water equipment; (*5*) technological equipment (pump, grinder, filter–separator, etc).

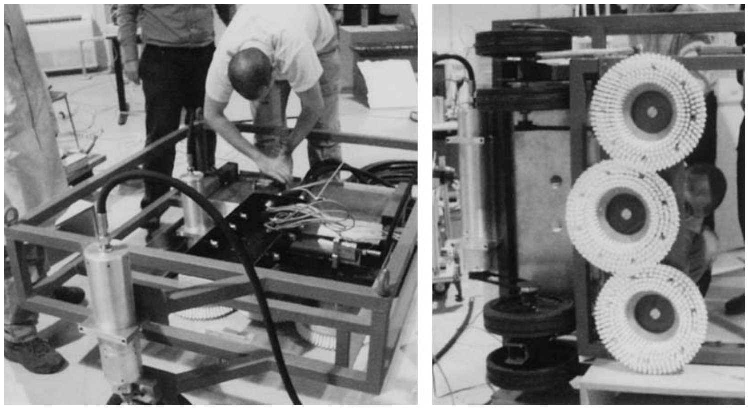

Fig. 8. Assembling of the AURORA underwater robot.

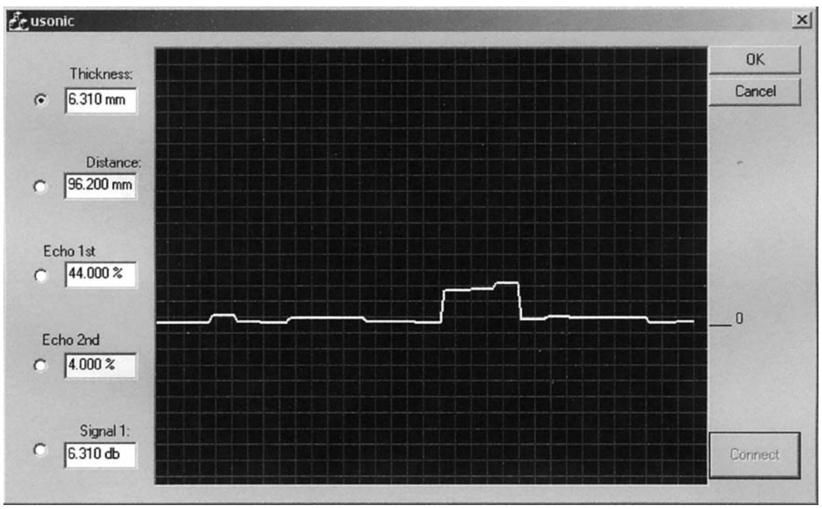

Fig. 9. Information on the sheet thickness of the ship's hull displayed on the operator's screen during the robot movement.

the ship's surface. The spring provides constant pressing of the passive wheel to the ship's surface. On the axle of the mechanism near the passive wheel, a Krautkramer ultrasonic probe is tightly fixed. In order to prevent breakage of the detector and the mechanism of its fixation to the robot if a substantial local obstacle is encountered, the top and bottom parts of the mechanism are connected by a cardan joint with ball locks and a recoil spring. If there is such a joint, at the moment when the additional wheel or probe contacts a local obstacle of substantial size, the joint folds, and then the recoil spring brings the joint into the initial state.

On the AURORA robot (Fig. 8), only one ultrasonic probe for measuring the sheet thickness of the ship's hull is mounted, but if more detailed studies of the sheet of the ship's hull are required, a line of these probes can be fixed on the robot in the same way, e.g., every 0.1 m.

An important feature of the considered system is the recording equipment on the control panel. This makes it possible to display on the operator's screen (Fig. 9) and record on-line the information about the sheet thickness simultaneously with the coordinates of the corresponding point. In this case, signals may be processed in the off-line regime, thinner sheet regions can be found, etc. Simultaneous recording of the image of the tested surface with the video camera allows one not only to find these areas, but also to visually estimate the state of the protective coating in them and thus to detect the side of the sheet on which corrosion is occurring, on the outer or inner surface, which makes it possible to decide on the most reasonable method of repair in this case.

One more special feature of the considered system is that the information on coordinates of the ship's surface makes it possible to reconstruct the real form of the underwater surface of the ship while it is afloat.

Note that, during shipbuilding and repair, the ship is in a dry dock and rests on supports under the keel. In this case, the forces of reaction of the supports are applied to a narrow zone, which significantly differs from the force distribution under the real sailing conditions of the ship. However, it is the real shape of the exterior surface of the ship that is important for estimating the stability of the ship and the resistance forces during its motion.

ACKNOWLEDGMENTS

We are grateful to the European Community Commission for financial support of this study as part of the AURORA project (contract no. G3RD-CT-2000-00246) and to all participants of the project working for the following organizations: IAI CSIC (Spain), Lund University (Sweden), SAIND (Spain), Riga Technical University (Latvia), Algosystems (Greece), Union Naval de Barcelona (Spain), and Kalogeridis I and T (Greece). We extend special thanks to A. Vatistas, T. Lilas, and A. Maglara.

REFERENCES

1. International Federation of Classification Societies. http://www.classificationsociety.org/
2. Journal "Dry-dock repair statistics," September 1998.
3. Journal "International ship repair news." September/October 1998.
4. T. Akinfiev, M. Armada, P. Gonzalez, and S. Ros, *Undersea robot and the control method therefore*, World patent, PCT publication N W 03042029.
5. Edahiro Kyouke, Development of Underwater Robot Cleaner for Marine Live Growth in Power Station, *Proc. of ICAR'83 International Conference on Advanced Robotics*, Tokyo, 1983, pp. 99–106.
6. Jones David, Afloat Maintenance, the Control of Marine Fouling and the Care of Coating Underwater. Book "Marine Coating," *32nd WEGEMT Summer School on Marine Coatings*, Publisher WGEMT, ISBN 1 900 453 118, David Short, Ed., 2000, pp. 205–217.
7. T. Akinfiev, M. Armada, R. Fernandez, Vehicle Control Method. World patent, PCT publication N W 03038387.
8. Krautkramer USM 25, http://www.krautkramer.com.au/prod01.htm