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Development and Application of a Novel Rail Runner Mechanism for Double Hull Structures of Ships

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Abstract— **Welding is very difficult and dangerous for manual welders. The double hull structures found in ships are very hazardous environments, and as such the shipbuilding industry demands a safer, autonomous system to perform the welding rather than deploy manual welders. This paper describes the design of a new mechanism, called the 'Rail Runner', which is able to autonomously travel within the double hull structure. The design of a 3P3R serial manipulator for welding is also described in this paper. As an application of the 'Rail Runner' mechanism, we combine the 'Rail Runner' platform and the 3P3R serial manipulator for autonomous welding. The mechanical system of this robot is composed of a six-axes (3P3R) manipulator for achieving the welding function and a six-axes mobile platform for traveling within the double hull structure. This robot is able to autonomously travel between longitudinal structures, with transverse direction, and is capable of welding in double hull structures. The 'Rail Runner' can raise the efficiency of the welding process, as compared to manual welders. This in turn raises the international competitiveness of the shipbuilding industry.**

I. INTRODUCTION

Recently , the need for autonomous welding operations has increased in shipyards as a way to improve both productivity and the working environment. Autonomous welding using multi-joint robots has been used in many applications since the 1990's. However, because these robots are able to work only at a fixed place, they need a worker's support to enable them to be moved to another work site. Therefore, a crane is usually used to move the welding robot to another site in the shipyard. However, such multi-joint robots are not able to work in a double hull structure because a crane cannot be fitted into them. This paper describes the development of an autonomous welding robot, using a novel mechanism that is able to travel in a double hull structure, which does not require a crane, or a gantry device, for its mobility.

A. Double Hull Structure of the Ship

For safe operation at sea, a ship must have the required structural stability to withstand a sea change or a sudden reef. As commercial ships carrying liquid cargo such as LNG (Liquefied Natural Gas), LPG (Liquefied Petroleum Gas) and crude oil can cause serious environmental pollution, ships such as VLCC (Very Large Crude oil Carrier), B/C (Bulk Carrier) and LNGC (Liquefied Natural Gas Carrier) incorporate a double hull structure which prevents outflow of cargo following an accidental collision or stranding (Fig. 1).

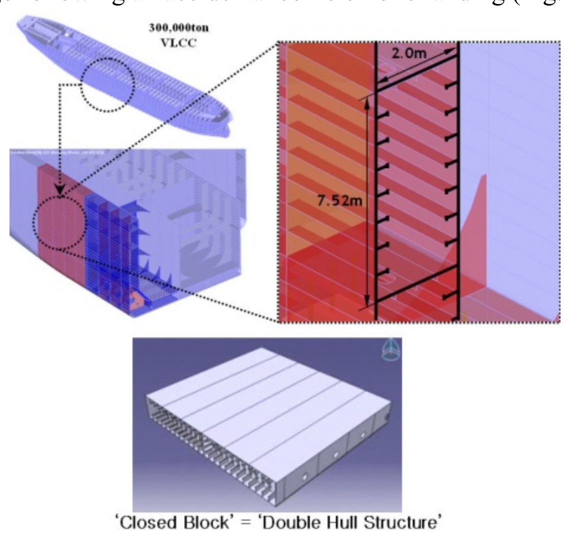

Fig. 1. Double hull structure in a ship

Due to the inherent advantages of such a double hull structure, its use has become increasingly common. However, its construction is more time-consuming and expensive due to its greater complexity than the single hull structure. In addition, it is difficult to weld, or paint, in a double hull structure due to it being an enclosed area and other associated working environment problems this creates. For these reasons, research has focused on autonomous work methods for the shipyard construction of double hull structures [1, 2, and 3].

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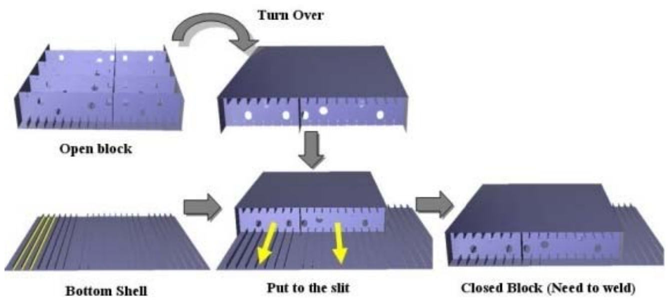

Fig. 2. Manufacturing of double hull structure

A double hull structure consists of top and bottom plates, girders and transverse web floors. The two plates cover the top and bottom of the double hull structure. The girder and transverse web floors divide the double hull structure into many closed sections. In each section, there are reinforcing longitudinal stiffeners arranged in parallel which, in turn, contain many small reinforcing stiffeners (Fig. 2).

B. Related works

Unlike a double hull structure, the automation of activities associated with the manufacture of single hull structures have been steadily developing in the shipyard industry; for example, there is a fixed, 6-axes robot called 'DANDY' [4]. This is one type of 6R manipulator which has been typically used in a single hull structure in Daewoo Shipbuilding & Marine Engineering, the Korean shipyard (Fig. 3). A worker uses this 6-axis robot for welding then moves it to the next welding location using an overhead gantry crane installed on the ceiling of the manufacturing factory. 'DANDY', however, cannot be used in the double hull structure as the gantry crane is not able to handle the robot in such an enclosed area.


Fig. 3. The use of DANDY for welding in open block

In the Hitachi-Zosen shipyard (Japan), an NC painting robot has been developed to paint inside the double hull structure [5]. This robot consists of a self-driving carriage, an expandable placer and a 6-axes manipulator. It is the 6-axes manipulator that carries out the painting.

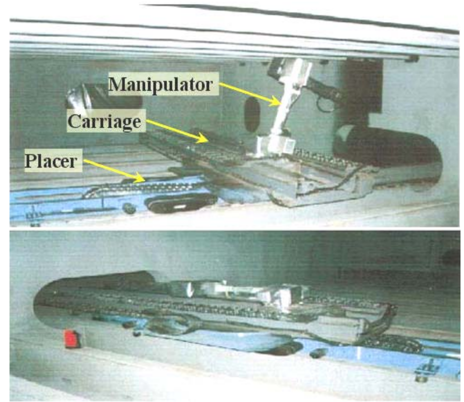

Fig. 4. Painting robot of HITACHI for the shipyard industry

The role of the placer is to move the manipulator to a suitable location in a division surrounded by floors and girders. The self-driving carriage, which mounts the placer and manipulator, runs on the faces of two longitudinal stiffeners without rails by utilising two sets of magnetic crawlers (Fig.4). There are, however, limitations to the robot's capabilities. The location of the 6-axes manipulator is limited by the reach of the placer in the transverse direction.

C. Objective of research

A double hull structure is composed of variable structures. A worker is able to move a fixed 6-axes robot to the next welding location, in a single hull structure, by using a crane (Fig. 5) but as already stated this cannot be done in double hull structures because of the enclosed space due to the upper plate (Fig 6).

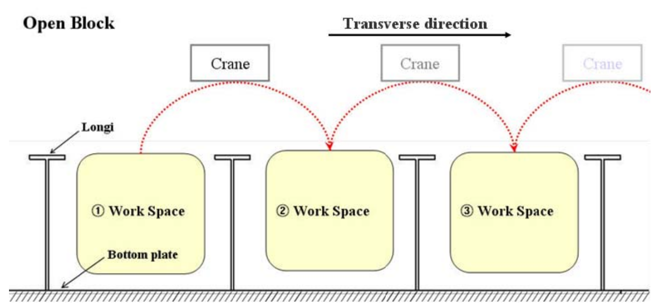

Fig. 5. Open block structure in single hulled ships

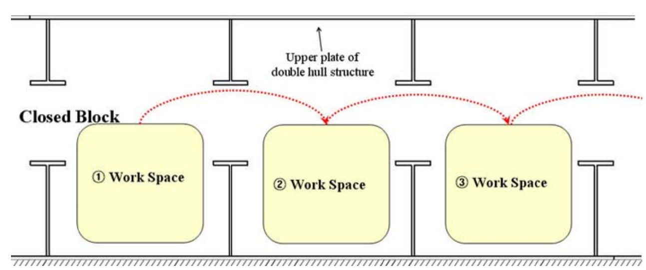

Fig. 6. Closed block structures in double hulled ships

Both single and double hull structures are composed of a longitudinal stiffener for the reinforcement of the structures, and a transverse web floor for connecting the upper and lower plates. The longitudinal stiffener becomes an obstacle, making a boundary line between the workspace (Fig. 5, Fig. 6) in automated welding applications.

Thus, in this paper, a 'Rail Runner' mechanism is designed for autonomously traveling in enclosed structures, such as those found in the double hull structures of ships. The mechanism presented is able to overcome the obstacle shown above, and is also able to weld the targets of the structures using a 3P3R manipulator.

II. DESIGN OF 'RAIL RUNNER' MECHANISM

A. Working Principal of 'Rail Runner'

A 'Rail Runner' mechanism enables a welding robot to autonomously move, in both longitudinal and transverse directions, in the double hull structure by being placed on the longitudinal stiffener. The longitudinal direction is the movement needed to transfer to the next workspace (Fig. 5, Fig. 6) and transverse direction is the direction of the slit shown in the Fig. 2.

The phases of the movements in transverse direction of the 'Rail Runner' mechanism are shown in Figure 7. The 'Rail Runner' platform is composed of an upper sliding section (top), a lower sliding section (center), and the driving wheel (below) (Fig. 8). The 'Rail Runner' platform is placed on the two longitudinal stiffeners at the initial state, supported by two points.

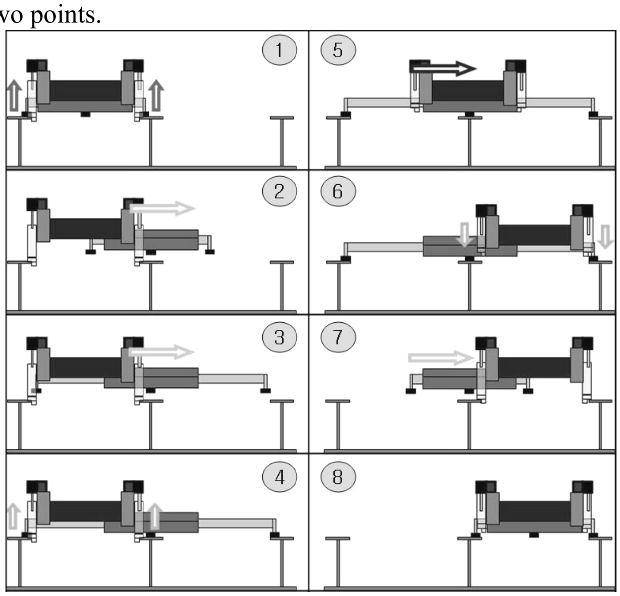

Fig. 7. Movement phases of the 'Rail Runner' mechanism

In Figure 7-2, the upper sliding section of this platform lifts the lower sliding section. This separates the lower sliding section from the longitudinal stiffeners, and then this part is able to move in the direction of the movement needed to transfer to the next workspace.

In Figure 7-3, the lower sliding section extends the two arms to a state supported by three points. In Figure 7-4, the two arms are extended by bisymmetry. Then the upper sliding section lowers the lower sliding section, and the upper sliding section is placed on the lower sliding section.

In Figures 7-5, and 7-6, the upper sliding section moves to the next workspace along the lower sliding section as if on a rail. Then, the upper sliding section lifts the lower one and the lower sliding section is separated from the longitudinal stiffeners. The rest of the movement process is the reverse of Figures 7-1, 7-2, and 7-3. The 'Rail Runner' platform is also able to move in the longitudinal direction using the longitudinal stiffener.

Both the longitudinal, and transverse direction movement of the 'Rail Runner' mechanism use the lower sliding section, and the longitudinal structure, like a rail, hence the name 'Rail Runner' is used.

B. Design of 'Rail Runner' platform

The mechanical combination of the 'Rail Runner' platform is shown, in exploded view, in Figure 8. There are three main assemblies, namely the upper sliding section (top), the lower sliding section (below), and the driving wheel section (center) (Fig. 8). It has 6-axes each driven by an AC servo motor and the travel of each servo axis is limited by micro switches, which are also used for calibration of the servos at start-up.

The upper sliding section has two functions. Firstly it is able to slide on the lower sliding section, and control the width between the driving wheels as the width of the longitudinal stiffener varies according to the kind of ship. Secondly the lower sliding section is able to extend two arms by bisymmetry, as already described above. The driving wheel section also has two functions, namely 1) it is able to drive the whole platform in a longitudinal direction and, 2) it can lift the whole platform up and down for the transverse movement.

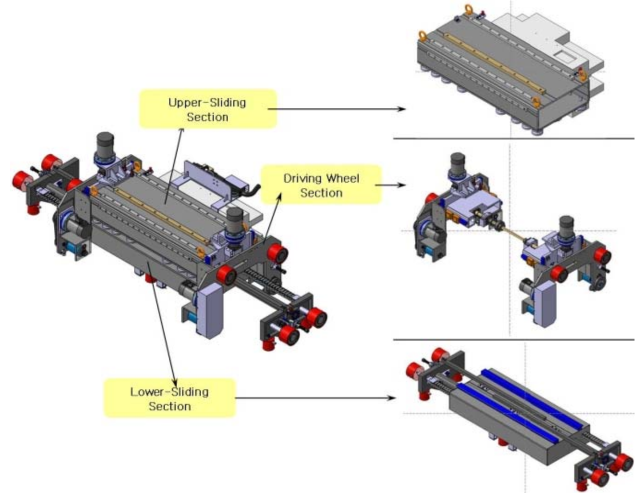

Fig. 8. Arrangement of the overall mechanical set up

III. DESIGN OF MANIPULATOR FOR WELDING

A. Design of '3P3R Manipulator' for Welding

The overall '3P3R (PPRPRR)' manipulator is shown in Figure 9. This manipulator is composed of 3-prismatic axes and 3-revolute axes. Each axis is driven by an AC servo motor, with the motion of each motions being limited by micro switches as well as for calibration at start-up. The arrangement of the degree of freedom, and the kinematic parameters, are shown in Figure 10.

The motors for all joints drives each joint via harmonic drive systems for reducing backlash and these operational ranges are shown in Table 2.

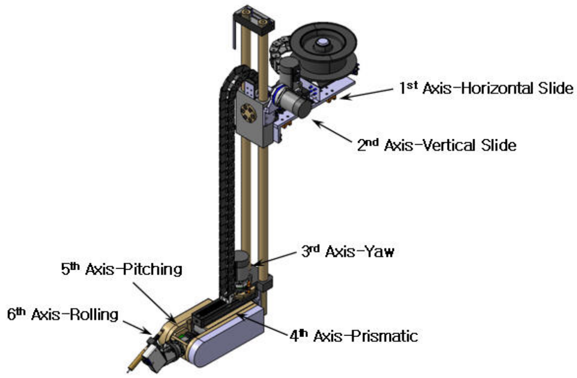

Fig. 9. Overall 3P3R manipulator

This manipulator has been designed to be able to carry a payload of up to 5kg for the welding operations. There is some equipment needed for performing this welding, such as welding wire spools and hence the manipulator is designed to be able to carry all the equipment needed so that workers only need to replace the welding wire spool when it has been depleted.

B. Kinematic Analysis

This section presents the architecture of the 3P3R manipulator, followed by the procedures describing the inverse and forward kinematics. As shown in Figure 10, the 3P3R manipulator consists of a PPRPRR serial chain that is fixed on the ‘Rail Runner’ platform. Here, P and R denote prismatic and revolute joints respectively. The manipulator has six degrees of freedom and six actuated joints. All the six actuated joints can be seen in Figure 10, and are indicated by arrows. The operational ranges of all the joints are shown in Table 2.

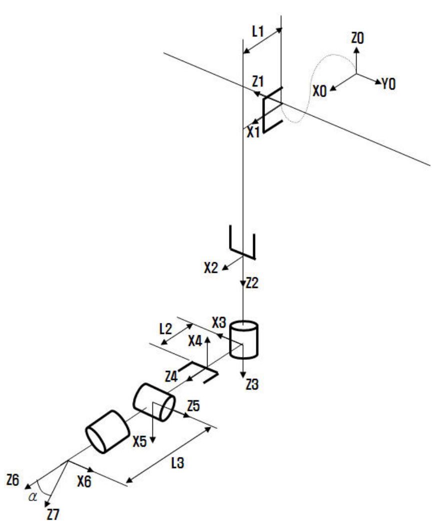

Fig. 10. Schematic diagram of the 3P3R manipulator (d is for the prismatic, and θ is for the revolute joint).

We have used the Denavit-Hartenberg parameters for solving the kinematics of the 3P3R manipulator (Table 1).

TABLE 1
DENAVIT-HARTENBERG PARAMETERS OF 6-DOF MANIPULATOR

JOINT I	α_{i-1}	a_{i-1}	d_i	θ_i
1	$\frac{\pi}{2}$	0	d_1	0
2	$\frac{\pi}{2}$	L_1	d_2	0
3	0	0	0	$\frac{\pi}{2}+\theta_3$
4	$\frac{\pi}{2}$	0	L_2+d_4	$-\frac{\pi}{2}$
5	$\frac{\pi}{2}$	0	0	$\pi+\theta_5$
6	$\frac{\pi}{2}$	0	L_3	$\frac{\pi}{2}+\theta_6$
T	α	0	0	0

α=30°, L_1 = 0, L_2 = 124.6, L_3 = 400

{T} is the tool frame of the welding torch and α is the torch angle relative to the 6th axis.

The problem of inverse kinematics is to determine the values of the actuated joints from the world position and orientation of the tool frame {T} attached to the moving platform. For the 3P3R manipulator, the inverse kinematics can be solved by successively solving the serial chain. The transformation matrix in this case is the following:

$$T_7^0 = T_1^0 \cdot T_2^1 \cdot T_3^2 \cdot T_4^3 \cdot T_5^4 \cdot T_6^5 \cdot T_7^6$$

$$T_7^0 = \begin{bmatrix} s_3c_6+c_3s_5s_6 & (c_3s_5c_6-s_3s_6)c_\alpha+c_3c_5s_\alpha & (-c_3s_5c_6+s_3s_6)s_\alpha+c_3c_5c_\alpha & s_3L_4+c_3c_5L_3+c_3L_2+c_3d_4+L_1 \\ c_3c_6-s_3s_5s_6 & (-s_3s_5c_6-c_3s_6)c_\alpha-s_3c_5s_\alpha & (s_3s_5c_6+c_3s_6)s_\alpha-s_3c_5c_\alpha & c_3L_4-s_3c_5L_3-s_3L_2-s_3d_4-d_1 \\ c_5s_6 & c_5c_6c_\alpha-s_5s_\alpha & -c_5c_6s_\alpha-s_5c_\alpha & -s_5L_3-d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$= \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \\ r_{41} & r_{42} & r_{43} & r_{44} \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{P} \\ \mathbf{0} & 1 \end{bmatrix}$$

1) The 5th joint value is calculated from the transformation matrix as follow:

$$\theta_5 = -\arcsin\left(r_{32}s_\alpha + r_{33}c_\alpha\right) \quad (2)$$

2) Calculate the revolute joint values, θ_3 and θ_6 (see Fig. 10), as follows:

$$\theta_3 = \arcsin\left(\frac{(r_{22}s_\alpha + r_{23}c_\alpha)}{-c_5}\right) \quad (3)$$

$$\theta_6 = \operatorname{arctan2}\left(\frac{r_{31}}{c_5}, \frac{r_{32}+s_5s_\alpha}{c_5c_\alpha}\right) \quad (4)$$

3) Determine the prismatic joint values, d_1, d_2 and d_4 [see Fig. 10], as follows:

$$d_1 = c_3 L_4 - s_3 c_5 L_3 - s_3 L_2 - s_3 d_4 - r_{24} \quad (5)$$

$$d_2 = -r_{34} - s_5 L_3 \quad (6)$$

$$d_4 = \left(\frac{r_{14} - s_3 L_4 - c_3 c_5 L_3 - c_3 L_2 - L_1}{c_3} \right) \quad (7)$$

where,

$$\begin{aligned} c_3 &= \cos(\theta_3), \quad s_3 = \sin(\theta_3) \\ c_5 &= \cos(\theta_5), \quad s_5 = \sin(\theta_5) \\ c_6 &= \cos(\theta_6), \quad s_6 = \sin(\theta_6) \\ c_\alpha &= \cos(\alpha), \quad s_\alpha = \sin(\alpha) \end{aligned} \quad (8)$$

The problem of forward kinematics is to determine the position and orientation of the world coordinates of the moving frame given the actuated joint values. The position and orientation values of the moving frame are found in the matrix of equation (1). The position values are:

$$p_x = r_{14},\ p_y = r_{24},\ p_z = r_{34} \quad (9)$$

C. Workspace Analysis

The workspace of a robot mechanism is defined as; the set of all positions and orientations that are reachable by the moving platform. The workspace analysis of the 3P3R manipulator begins with a description of the moving frame and its orientation. Many parameterizations exist for describing the orientation; e.g., Euler angles, fixed angles, exponential coordinates, etc. Due to the simple architecture of the 3P3R manipulator, it was decided to describe the orientation of the mechanism using the z-y-x Euler angles. In terms of these, the rotation matrix is given by;

$$R = Rot_Z(\alpha) \cdot Rot_Y(\beta) \cdot Rot_X(\gamma)$$

where α, β, and γ are the rotation angles, in succession, about the z, y, and x axes. The actual Cartesian workspace is restricted by the following physical constraints on the mechanism:

1. Stroke limit of the linear prismatic joints;
2. Interference between the vertical columns;
3. Rotation limit of the revolute joints;

The operational range of each joint is shown in Table 2.

TABLE 2
OPERATIONAL RANGE OF EACH JOINT

JOINT I	MAXIMUM VALUE	MINIMUM VALUE
1	220.0 mm	-220.0 mm
2	870.0 mm	0 mm
3	$\frac{1}{2}\pi$	$-\frac{1}{2}\pi$
4	229.5 mm	0 mm
5	$\frac{1}{2}\pi$	$-\frac{1}{2}\pi$
6	π	$-\pi$

The results of workspace analysis are shown in Fig. 11. The "reachable workspace' is the larger area enclosing the other two workspaces, namely; "task-oriented workspace" and "task workspace." The reachable workspace is a set of positions that the welding torch tip can approach without considering the possible orientation angle. This means that, in certain positions, the orientation can be limited. The task-oriented workspace is a set of positions that the welding torch tip can approach with the capability of the orientation angles whose orientation axis can be confined to a cone with its aperture angle of 60°. Finally, the task space is a set of required welding tip positions to weld the U-shape path.

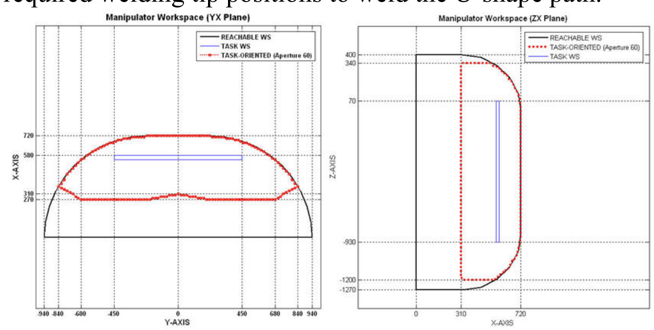

Fig. 11. Result of the workspace analysis in the *y-x* and *z-x* planes

IV. APPLICATION OF 'RAIL RUNNER' MECHANISM

As above, the 3P3R manipulator is designed for welding, and the 'Rail Runner' mechanism is designed for autonomously traveling in the double hull structure. Figure 12 shows the combination of these two assemblies together with an overview of the mobile welding robot. The first axis of the 3P3R manipulator is coupled by an LM (Linear Motion) guide at the top plate of the 'Rail Runner' platform. Two rails of the LM guide are attached to the top plate of the 'Rail Runner' platform, and four blocks of the LM guide are attached under the plate of the 1st axis (Fig. 12).

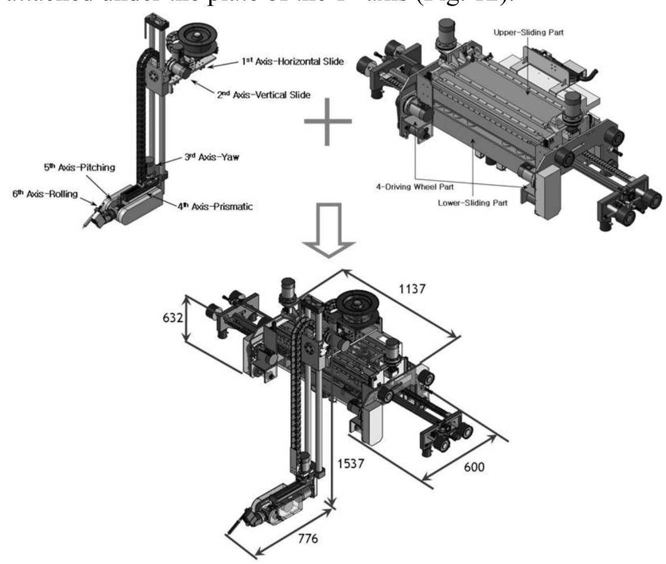

Fig. 12. Combination of 'Rail Runner' platform and '3P3R' manipulator for welding

Figure 12 shows a photograph of the manufactured mobile welding robot. And specification of ‘Rail Runner’ is shown in Table 3.

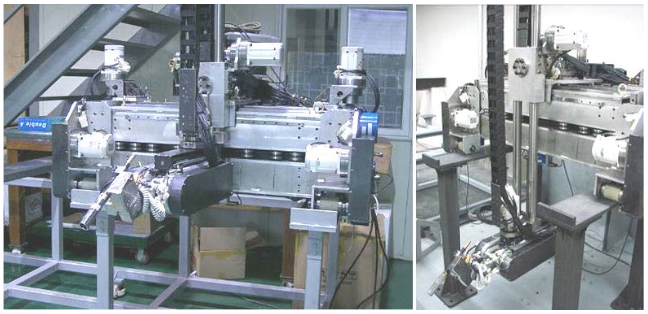

Fig. 13. Manufactured ‘Rail Runner’ welding robot

TABLE 3
SPECIFICATION OF ‘RAIL RUNNER’ WELDING ROOT

Size	1,137mm(L)×600mm(W)×1,537mm(H)		
Weight	Manipulator	83.1 kg	353.0 kg
	Mobile platform	269.9 kg	
Payload	5.0 kg		
Velocity	longitudinal direction	4.3m/min	
	transverse direction	1cycle/2.5 min	
	Time for welding the U-shaped part	26 min	

V. CONTROL SYSTEM

The control system consists of a main controller, a welding machine controller (arc sensor board), and seam tracking sensors, i.e. touch sensor, laser sensor and arc sensor (Fig. 14). To execute the welding process, the main controller needs to control the robot and the welding machine, which supplies the electric power for welding, simultaneously. Because the main controller is mounted on the mobile platform, we developed a welding machine controller, called ‘arc sensor board’ which is installed near the welding machine.

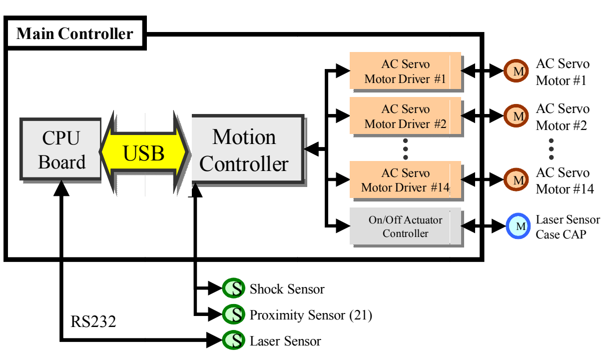

Fig. 14. Configuration of the control system of ‘Rail Runner’

The main controller communicates the welding information with the welding machine controller through RS485 communication. The configuration of the control system is shown in Fig. 14.

A. Main controller

If the main controller is located outside of the double hull structure, the robot should drag ‘very long’ motor power cables and motor encoder cables. To avoid this problem, we designed the main controller mounted on the back of the mobile platform (Fig. 15).

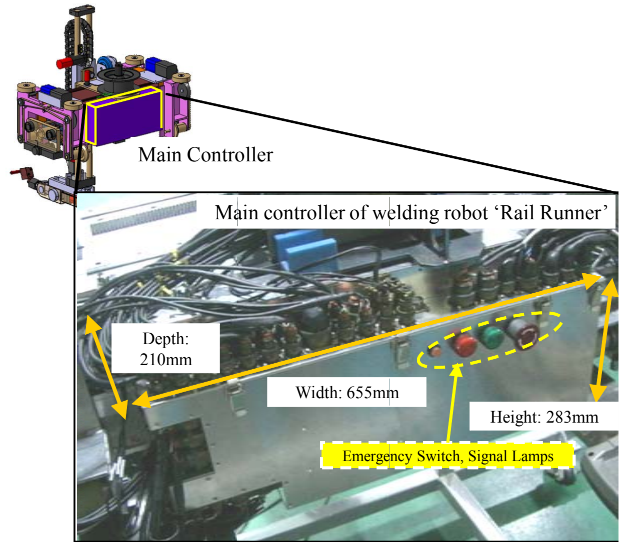

Fig. 15. The main controller in the control system of ‘Rail Runner’

The main controller consists of a CPU board, a motion controller which can execute linear interpolation for all of 14 axes and 14 AC servo motor drivers. The CPU board calculates welding start points and end points, generates welding path, and calculates the angles of all joints of the robot.

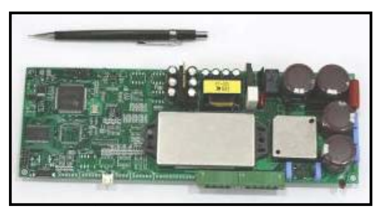

Fig. 16. The AC servo motor driver (230mm width x 90mm height x 20mm depth) in the main controller of ‘Rail Runner’

The motion controller receives the commands from CPU board, and then controls the 14 AC servo motor drivers, which control the 14 AC servo motors. Fig. 16 and 17 show the configuration of the AC servo motor drivers and a motion controller.

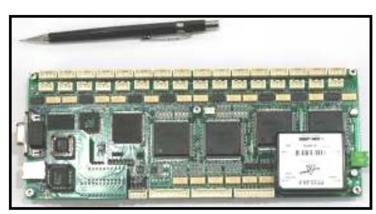

Fig. 17. The motion controller (230mm width x 90mm height x 20mm depth) in the main controller of ‘Rail Runner’

VI. VERIFICATION OF THE DEVELOPED ROBOT ON A TEST BLOCK

To verify the motion ability and welding quality of the developed 'Rail Runner' robot, a test block was constructed, made of longitudinal stiffeners, and other stiffeners, to reinforce the longitudinal stiffeners. Fig. 18 shows the results of the self-driving movement in the transverse direction of the 'Rail Runner' to verify its motion capability. The 'Rail Runner' stretches its sliding arms to the next longitudinal stiffener (Figs. 18-1 and 18-2), then moves on the next longitudinal stiffener (Figs. 18-3 and 18-4), and then draws in its sliding arms (Figs. 18-5 and 18-6). It takes the 'Rail Runner' approximately 1.5 minutes to move to the next longitudinal stiffener, while it takes 'DANDY' approximately 1 minute. Moreover, the 'Rail Runner' moves autonomously while 'DANDY' requires manual operation of a gantry crane, in order to be moved as already explained.

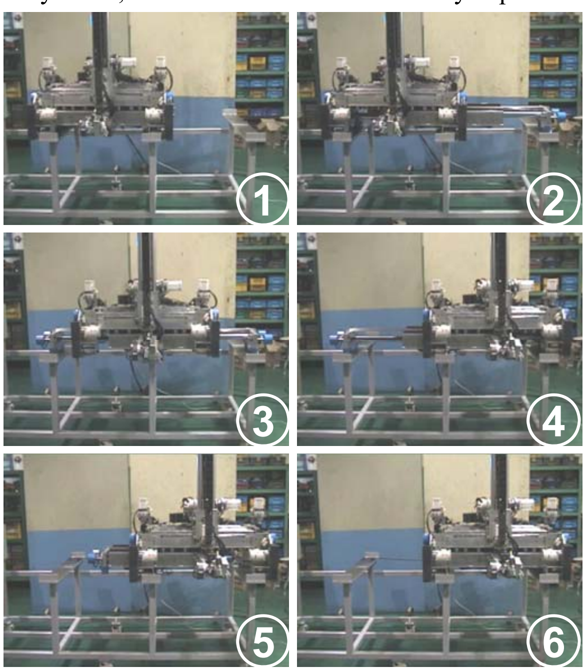

Fig. 18. Test results of the movement in the transverse direction of 'Rail Runner'

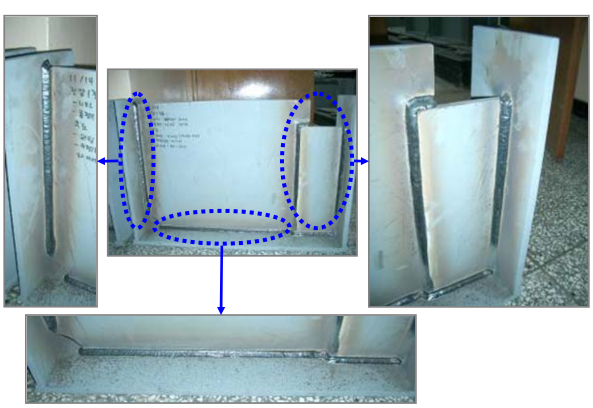

Fig. 19. Welding test results from using the 'Rail Runner'

VII. CONCLUSION

This paper describes the development of a new design of self-driving mobile welding robot, called the 'Rail Runner', which can move, and weld, in double hull ship structures. To verify the motion capability and welding quality of the developed robot, the longitudinal, and transverse, movements of the robot, as well as the welding quality, were tested on a test block, and were determined to be satisfactory. The major limitation of the 'Rail Runner' is that it cannot be easily handled due to its excessive weight (353kg). Future research will be focused on reducing its weight and also developing a device for placing the 'Light Rail Runner' into double hull ship structures.

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