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Design of controller for mobile robot in welding process of shipbuilding engineering

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Abstract

The present study describes the development of control hardware and software for a mobile welding robot. This robot is able to move and perform welding tasks in a double hull structure. The control hardware consists of a main controller and a welding machine controller. Control software consists of four layers. Each layer consists of modules. Suitable combinations of modules enable the control software to perform the required tasks. Control software is developed using C programming under QNX operating system. For the modularizing architecture of control software, we designed control software with four layers: Task Manager, Task Planner, Actions for Task, and Task Executer. The embedded controller and control software was applied to the mobile welding robot for successful execution of the required tasks. For evaluate this imbedded controller and control software, the field tests are conducted, it is confirmed that the developed imbedded controller of mobile welding robot for shipyard is well designed and implemented.

Keywords: Mobile welding robot; Modularized control architecture; Embedded controller; Industrial automation

1. Introduction

The need for autonomous welding tasks has increased recently in shipyards to improve productivity. Autonomous welding tasks using multi-axis robots have been used in many applications since the 1990s. However, the robots work only at a fixed location, and a crane is usually used to move the robots from one working location to another [1-4]. Therefore, we developed a self-driving mobile welding robot, which does not require a crane or a gantry device for mobility, in a ship's double hull structure.

This paper describes the development of control hardware and control software for a mobile welding robot that moves in transverse and longitudinal directions (Moving Tasks), performs welding tasks within the U-shaped welding areas and the brackets in a double hull structure (Welding Tasks), and detects the start and end points of the welding path (Sensing Tasks).

1.1 Double hull structure in a ship

Tankers, container carriers, liquefied natural gas carriers, and liquefied petroleum gas carriers should be provided with a double hull structure to maintain structural stability and to prevent environmental pollution caused by accidental collisions or stranding. Figure 1 shows the double hull structure of a very large crude oil carrier.

It is difficult to automate the manufacturing process of the double hull structure because of the enclosed area associated with increased compartmentalization for environmental safety. For these reasons, many studies have focused on automating the manufacturing process of the double hull structures in shipyards [5].

1.2 Welding target in a double hull structure and accessibility

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 girders and transverse web floors divide the double hull structure into a number of closed sections. In each section, several reinforcing longitudinal stiffeners are arranged parallel to each other and these contain many small reinforcing stiffeners. Figure 2 shows the welding targets of the proposed robot (U-shaped part). The welding targets are located on both the top and bottom of the block. When the block is the open type, only one side is a welding target; the other side becomes a welding

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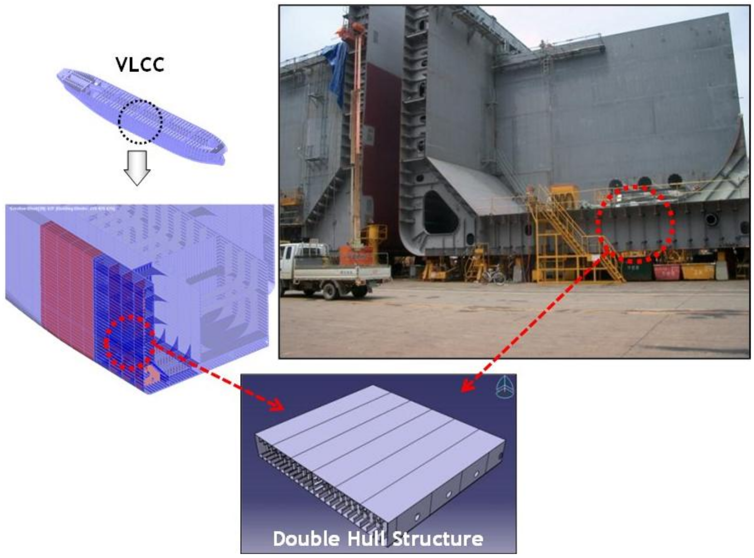


Figure 1. Double hull structure of a very large crude oil carrier (VLCC).

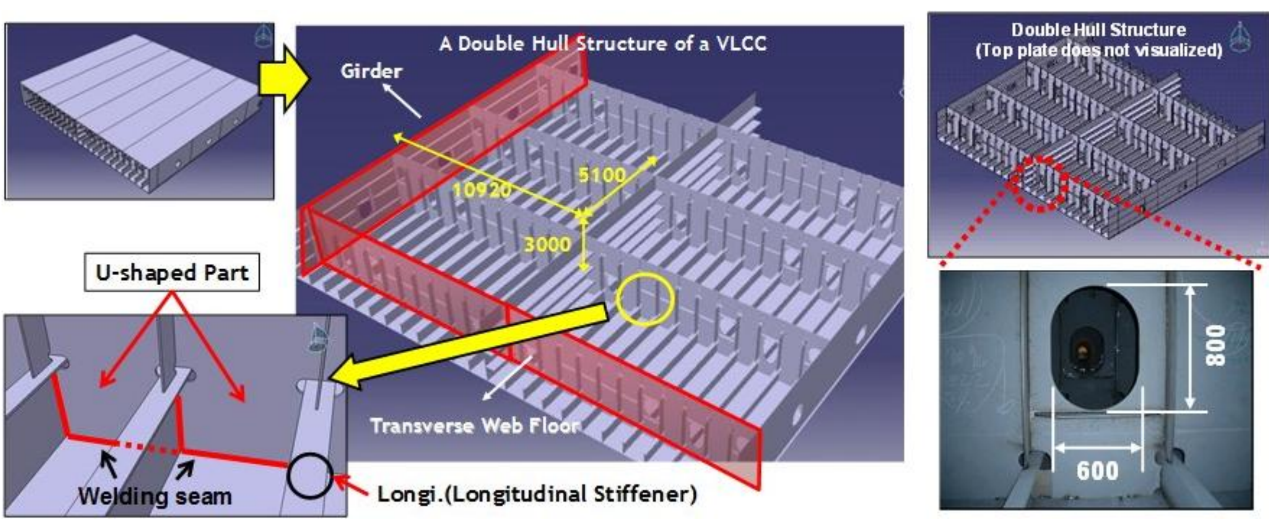


Figure 2. Welding target in a double hull structure and access hole on the transverse web floor in a double hull structure.

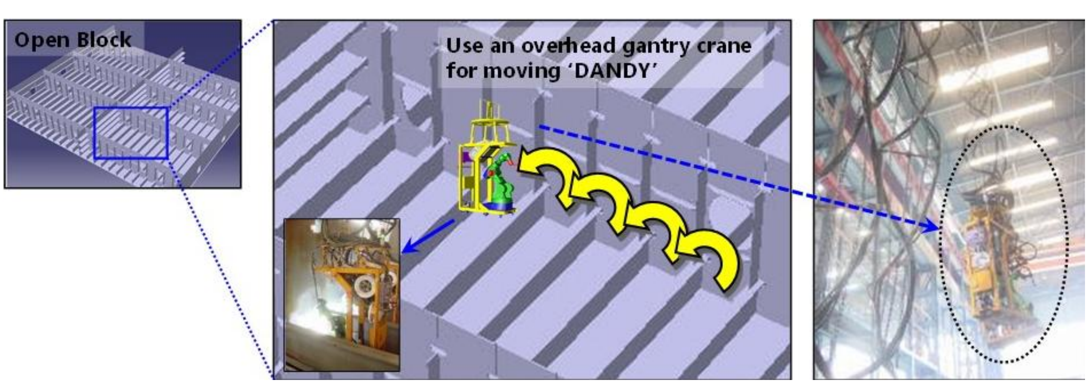


Figure 3. DANDY, a fixed welding robot used by Daewoo Shipbuilding & Marine Engineering in Korea.

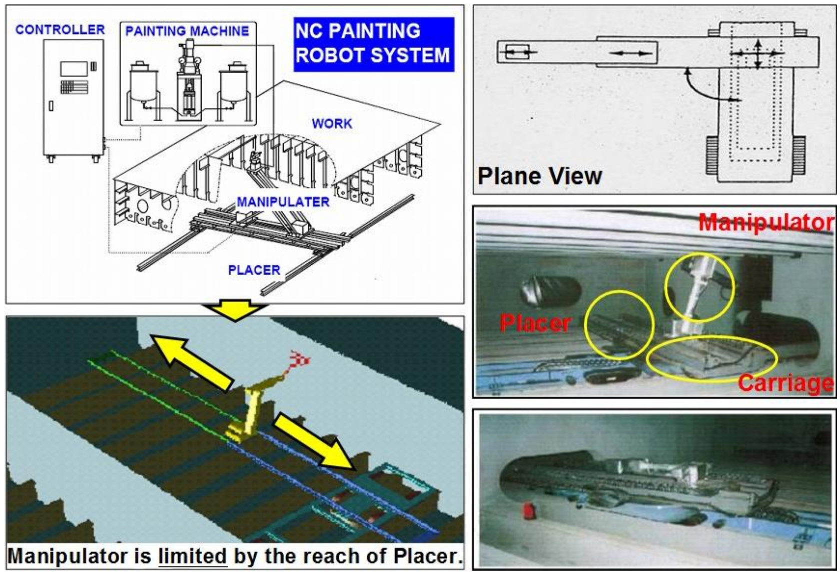


Figure 4. NC painting robot in the Japanese shipyard Hitachi-Zosen.

target after the block becomes the closed type. For this reason, the proposed robot needs to be operated inside the closed block.

The self-driving mobile welding robot moves in longitudinal and transverse directions and welds U-shaped areas in the double hull structure. To place the robot in the double hull structure, the robot passes through an access hole with dimensions of 600 mm width × 800 mm height.

2. State of arts

2.1 Welding target in a double hull structure and accessibility

The robot welding system with a fixed multi-axis robot is used in single hull structures in many shipyards. For example, as shown in Figure 3, a fixed six-axis robot called DANDY is used to weld single hull structures automatically by Daewoo Shipbuilding & Marine Engineering in Geoje, Korea [6]. An

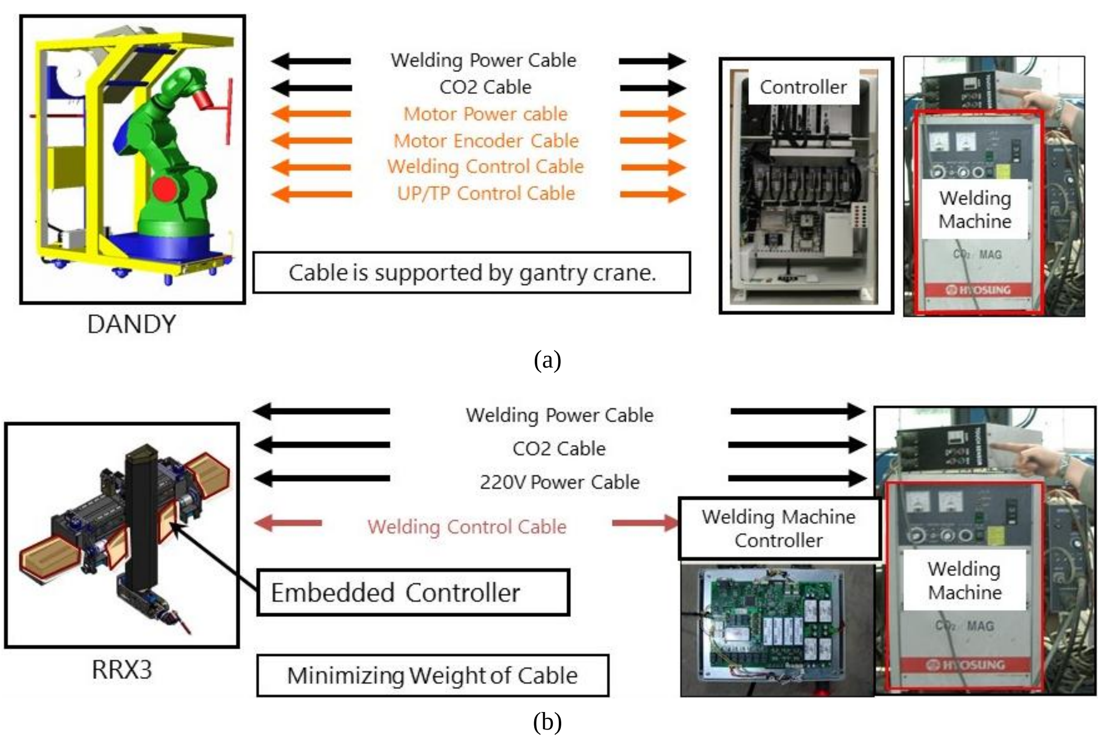


Figure 5. The cables between the controller and the welding robot (DANDY, RRX3): (a) cable between controller and fixed type welding robot 'DANDY', (b) cable between controller and mobile welding robot 'RRX3'.

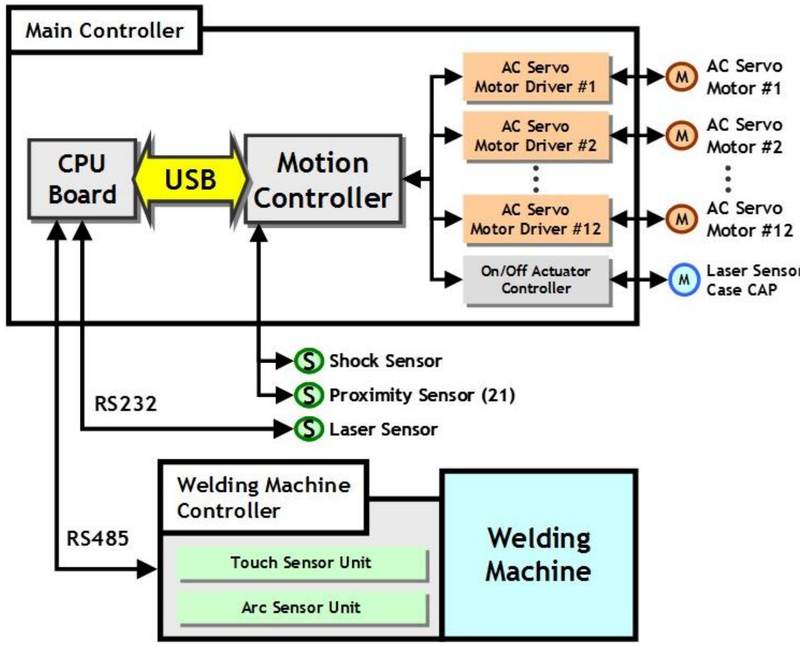


Figure 6. Configuration of the embedded controller for RRX3.

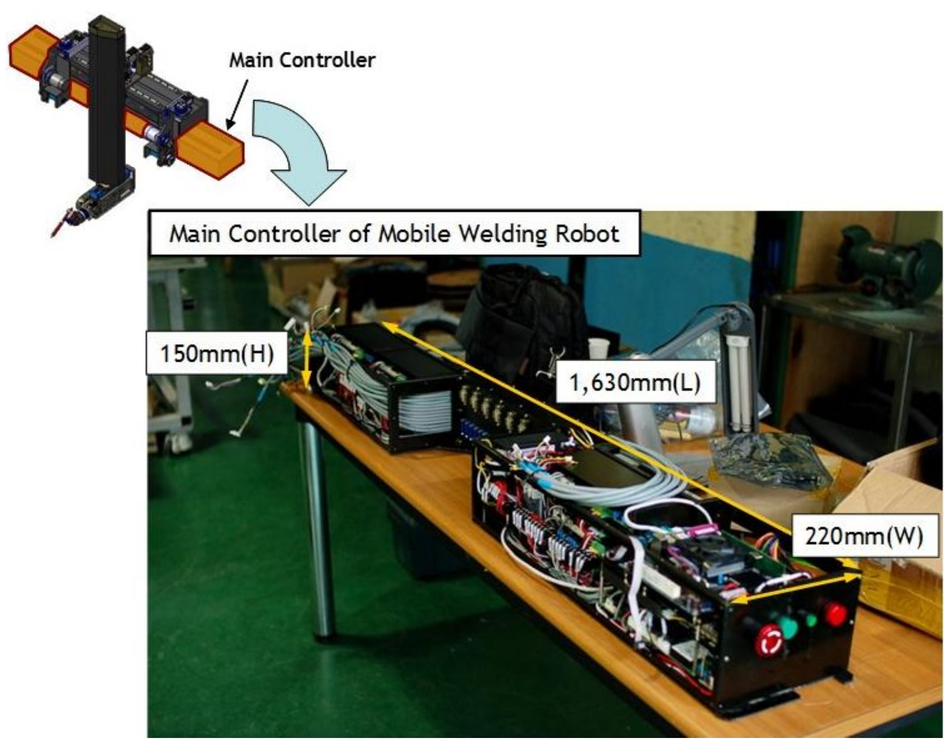


Figure 7. The main controller for RRX3.

overhead gantry crane installed on the ceiling of the manufacturing factory moved DANDY between welding locations. DANDY, however, cannot be used in a double hull structure because the gantry crane is not able to handle the robot in such an enclosed environment.

In Hitachi-Zosen, a shipbuilding company in Japan, an NC painting robot was developed to paint inside the double hull structure [5]. This robot consists of a self-driving carriage, an expansible placer, and a six-axis manipulator used for painting. The placer moves 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 utilizing two sets of magnetic crawlers, as shown in Figure 4.

The robot has two limitations. First, the reach of the placer

(a)

(b)

Figure 8. Motor driver and motion controller in the main controller of RRX3: (a) AC servo motor driver (230 mm width × 90 mm height × 20 mm depth), (b) motion controller (230 mm width × 90 mm height × 20 mm depth).

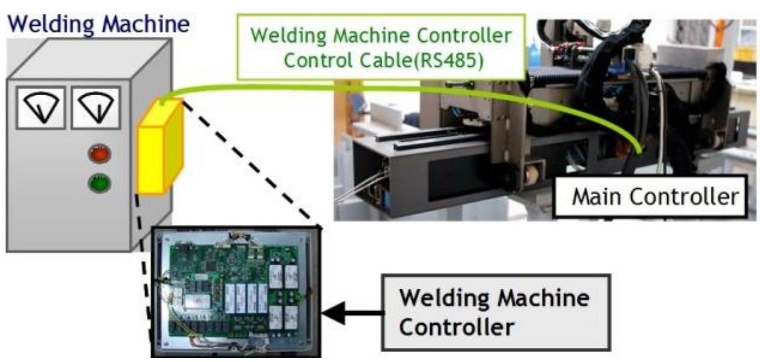


Figure 9. Connection between the welding machine controller and the main controller of RRX3.

in the transverse direction limits the location of the six-axis manipulator. Second, the size of the robot is too large to pass through an access hole with dimensions of 600 mm × 800 mm, so each web floor needs a permanent opening with dimensions of 1600 mm × 800 mm, thus changing the structural design.

Kim et al. [7] developed the robot system "RRX3" for welding in a double structure. For mobility of this welding robot, the imbedded controller has been specially developed. The differences between related robots and the system proposed in this paper are presented in Table 1.

2.2 Why an embedded controller for RRX3?

In order to perform the Welding Tasks, the welding robot needs to be able to move independently in longitudinal and transverse directions. In the case of the DANDY, the fixed 6 axis welding robot developed by DSME, the controller is located 50 m away from the welding robot. Consequently, a lengthy motor power cable and motor encoder cable are required between the controller and the robot, and the gantry

Table 1. Features of different systems analyzed in this study.

	RRX3	DANDY	NC painting robot
Operation in open block	Possible	Possible	Possible
Operation in closed block	Possible	Impossible	Possible
Passing through access hole	Possible	Impossible	Possible
Size of access hole	600 mm × 800 mm	-	1,800 mm × 800 mm
Controller	Embedded	Located outside of the block	located outside of the block

crane must sustain the weight of the cables. However, in the double hull structure, RRX3 drags the cables without using the crane. Therefore, an embedded-type controller has been developed to minimize the number and the weight of the cables. Figure 5 shows the compositions of the cables for RRX3 and DANDY.

2.3 Modularizing control software

The modularizing of the unit function of the robot has been studied in order to easily add new hardware such as sensors [8] and to perform repeatable tasks efficiently [9]. In addition, a three layer architecture has been studied for real-time performance [10, 11]. Software architecture based on hybrid control architecture has also been studied [12].

In this study, the control software adapts the hybrid control architecture of [12]. Furthermore, the mobile welding robot is connected to multiple hardware including servo motors, sensors and welding machines. Since industrial robots require high accuracy to prevent mistakes and problems, the control software must be robust. Therefore, this study develops control software using modularized control architecture [8, 9].

3. Modularized control architecture of the embedded controller for RRX3

3.1 Embedded controller for RRX3

The control hardware of RRX3 consists of the main controller and the welding machine controller. The main controller is mounted on the RRX3 and controls the AC servo motors and the sensory systems (proximity sensor, laser sensor, and shock sensor). The welding machine controller is attached to the welding machine for accurate control (Figure 6).

3.1.1 Main controller

If the main controller is located away from the robot, the mobile welding robot needs to drag lengthy motor power and encoder cables. In order to avoid this, the controller is mounted underneath the RRX3, as shown in Figure 7.

The main controller consists of a CPU board, a motion controller (which is able to execute linear interpolation for all 12 axes), and 12 AC servo motor drivers. The CPU board is 866LCDM/mITX, a commercial product manufactured by KONTRON. It has robot control software that has been developed through this study. The motion controller receives commands from the CPU board, and controls the 12 AC servo motor drivers. The motion controller and the AC servo motor drivers have also been developed through this study. RRX3 has motors manufactured by Panasonic. However, the size of Panasonic's commercial AC servo motor driver is too large to be placed in the embedded main controller, which prompted us to develop the motion controller and the AC servo motor drivers. The drivers are the incremental type. Figure 8 shows the AC servo motor drivers and the motion controller used on the controller of RRX3.

3.1.2 Welding machine controller

In the case of DANDY, which is a fixed-type welding robot, the main controller and the welding machine are located close to each other. Accordingly, there is no limitation for the controller to manipulate the analog voltage, which is the input and output data of the welding machine. However, as the length of cable between the main controller and the welding machine increases, it becomes more difficult for the main controller to correctly manipulate the analog voltage, due to the effects of the voltage drop and noise. Therefore, in this study, the welding machine controller in Figure 9, which controls the welding machine, is developed and attached to the welding machine.

The welding machine controller has an arc sensor, which has been developed by DSME. It can therefore ensure that the welding torch follows the desired welding path. The intensity of the electric current during welding is inverse proportional to the distance between the torch and the welding area. The welding machine controller uses this current to calculate the distance between the torch and the welding area and to decide whether the work has been successfully accomplished.

3.2 Control software architecture for RRX3

RRX3 performs Moving Tasks and Welding Tasks that require high accuracy (error range: under 0.5 mm). In order to control the welding robot, the 'actions' of the welding robot are defined. A suitable combination of 'actions' enable the control software to perform the various tasks required.

3.2.1 Modularized control software architecture

Control software consists of four layers: Task Manager, Task Planner, Actions for Task, and Task Executer.

- Task Manager: Manages the task list provided by the users, and communicates with the Teaching Pendant (TP).
- Task Planner: Receives tasks from the Task Manager and chooses the 'actions' in Actions for Task.
- Actions for Task: Receives 'actions' from the Task Planner and generates the trajectory of the robot by using environmental data and robot status data, which is provided by the Task Executer.
- Task Executer: Controls the motion controller and the actuator. The Task Executer controls the robot to execute the tasks and receives environmental data and robot status data from the sensors.

The tasks can be performed through combinations of 'actions' chosen by the Task Planner in Actions for Task. Furthermore, the unit functions of the Task Executer are modularized for new hardware to be easily added. Figure 9 is a schematic of the four layers and modules that compose the control software.

3.2.2 Task planner

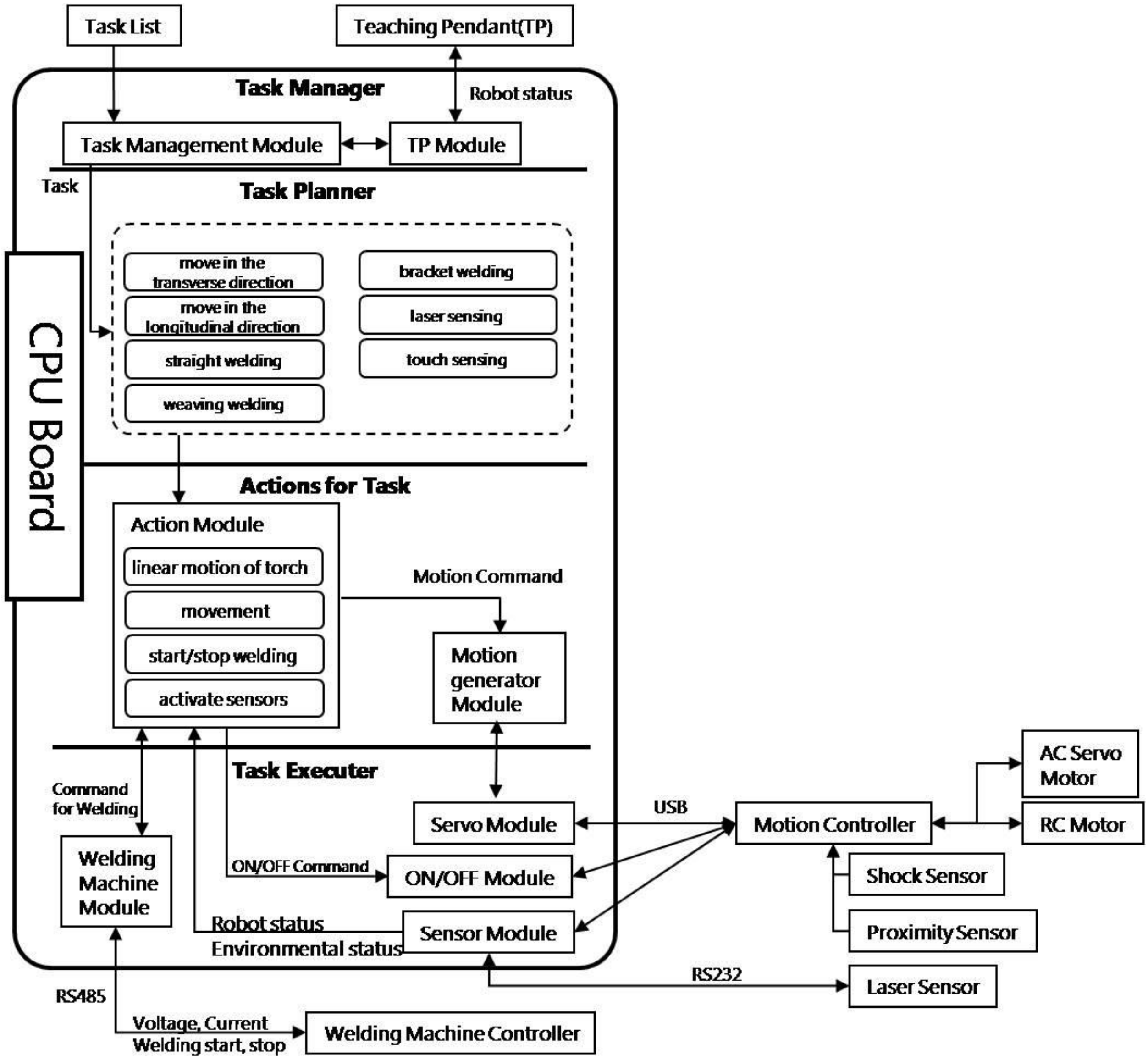


Figure 10. The four layer architecture and modules of RRX3.

The Task Planner performs tasks provided by the Task Manager while combining 'actions' in Actions for Task. The functions of the Task Planner correspond to each task as follows:

(*a*) '*Move in the Transverse Direction*' and '*Move in the Longitudinal Direction*' (*Moving Tasks*)

The Task Planner performs Moving Tasks by combining 'activate sensors' and 'sequential motor control for transverse movement' or combining 'activate sensors' and 'sequential motor control for longitudinal movement' in Actions for Task. The concrete procedures of the moving tasks are shown in Section 4.1 and Section 4.2.

(*b*) *Straight Welding, Weaving Welding, and Bracket Welding* (*Welding Tasks*)

The Task Planner performs the Straight Welding Task and the Weaving Welding Task by combining the 'linear motion of torch' and 'start/stop welding' in Actions for Task. The concrete procedures of the Weaving Welding Tasks are shown in Section 4.3.

(*c*) *Laser Sensing and Touch Sensing* (*Sensing Tasks*)

The Task Planner performs Sensing Tasks by combining 'activate sensors' and 'linear motion of torch' in Actions for Task.

3.2.3 Modules of actions for task

Actions for Task executes 'actions' that are required by the Task Planner. Actions for Task generates the trajectory of the welding torch. At the same time, this layer communicates with the laser sensor, the proximity sensor, and the shock

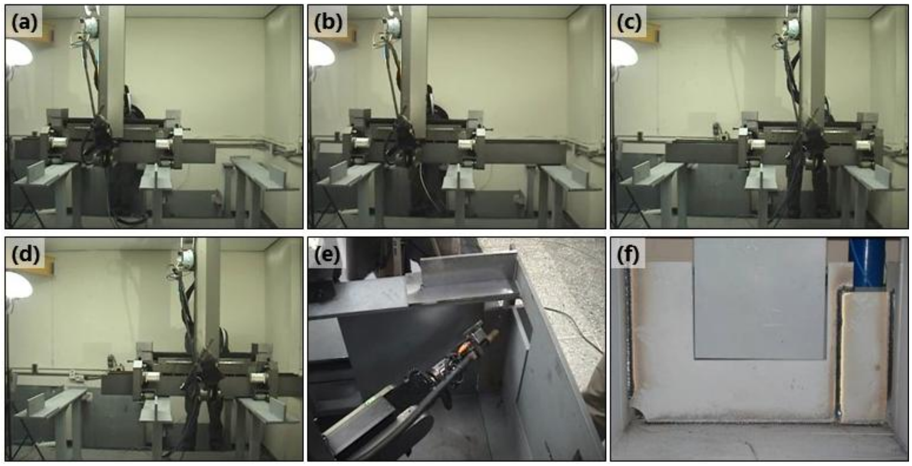


Figure 11. Test (movement and welding) results of RRX3: (a) start of movement to the transversal direction, (b) moving sub-body including main controller to the transversal direction, (c) moving main-body to the transversal direction, (d) completion of transversal movement, (e) sensing and welding an U-shaped parts, (f) result of welding an U-shaped parts.

sensor in order to receive environmental data, such as the existence of the longitudinal stiffener (longi.) or the distance between the welding robot and the U-shaped welding areas. When the welding robot performs the Welding Tasks, Actions for Task starts or stops the welding, while executing other 'actions'.

There are two types of modules in Actions for Task, the Action Module and the Motion Generator Module.

3.2.3.1 Action module

The Task Planner selects suitable 'actions' in the Action Module. The Action Module then transfers the command to other modules in the Task Executer, which correspond to the 'actions' selected by the Task Planner. The functions that correspond to each 'action' are as follows:

(*a*) '*Linear motion of the torch*'

The Action Module transfers the motion command to the Motion Generator Module, which in turn generates the trajectory of the welding torch, and transfers the angle data of each motor to the Servo Module in Task Executer. 'Linear motion of torch' is necessary 'action' to perform tasks (Weaving Welding, Bracket Welding, Touch Sensing, etc.) that are related to the motion of the welding torch.

(*b*) '*Sequential motor control for transverse movement*' and '*sequential motor control for longitudinal movement*'

The Action Module controls the Servo Module to perform

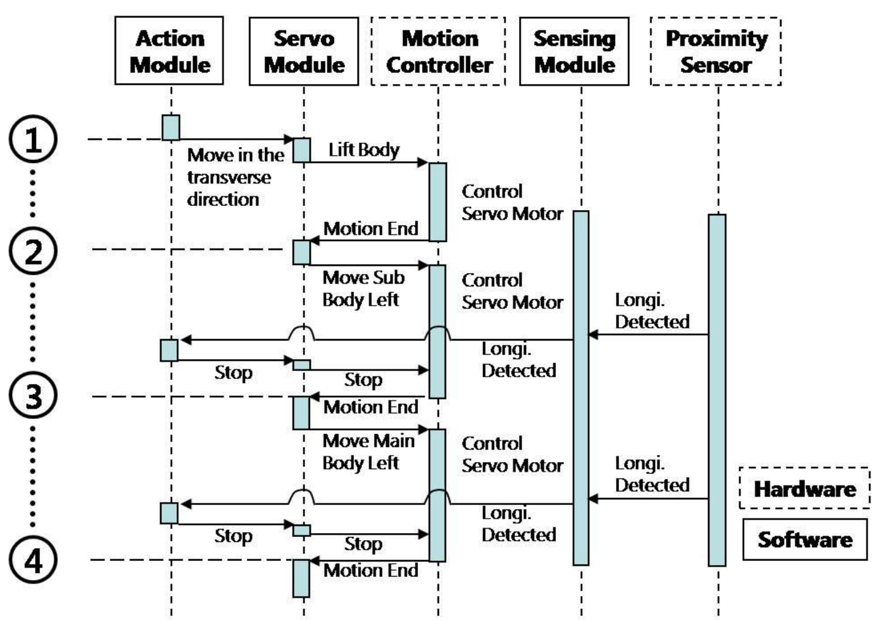


Figure 12. Data transfer sequence between modules during movement in the transverse direction.

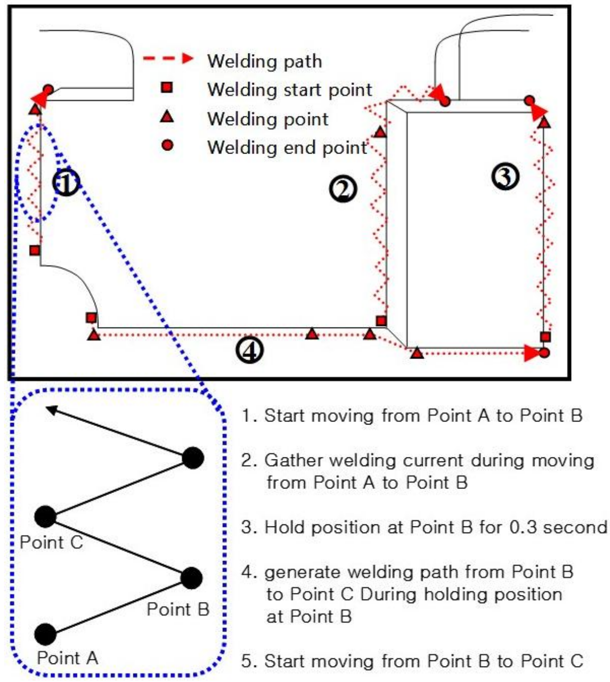


Figure 13. Weaving welding sequence.

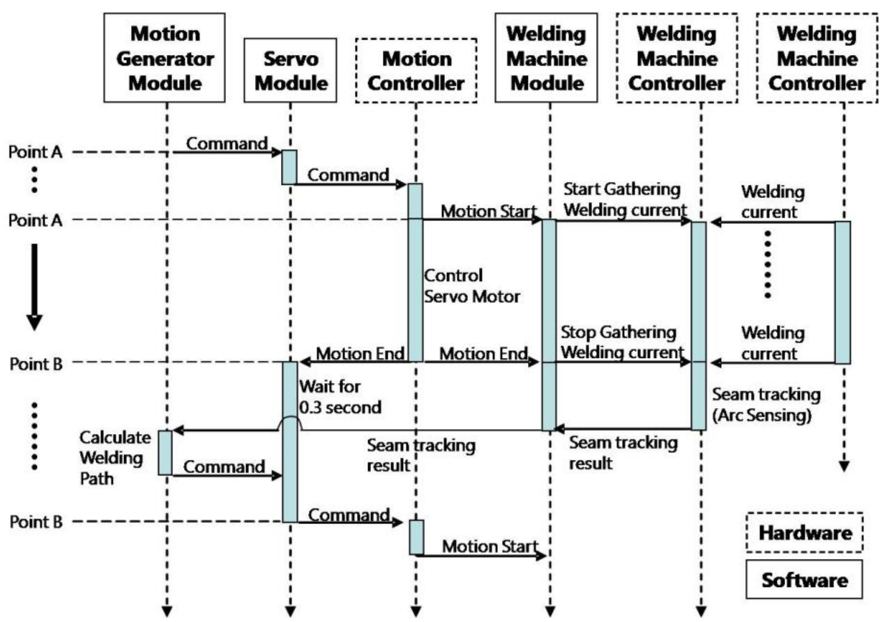


Figure 14. Data transfer sequence between modules during weaving welding.

Moving Tasks, using environmental data from the Sensor Module. 'Sequential motor control for transverse movement' and 'sequential motor control for longitudinal movement' are necessary 'actions' to perform tasks (Move in the Transverse Direction, Move in the Longitudinal Direction, Bracket Welding) that are related to the movement of the welding robot.

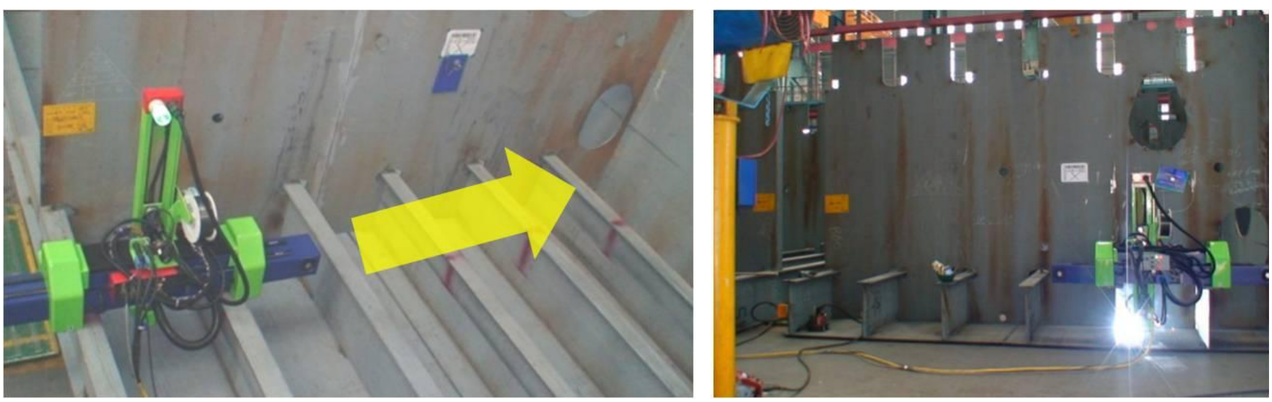
(*c*) '*Start / stop welding*'

This Action Module transfers the welding voltage and current data to the Welding Machine Module.

(*d*) '*Activate sensors*'

The Action Module transfers the sensing command to the Sensor Module in the Task Executer. The Action Module uses sensing data from the Sensor Module to generate the next movement by the welding robot. 'Activate sensors' is necessary 'action' to perform Moving, Welding, and Sensing Tasks.

Figure 15. Welding results of the welding test for the mobile welding robot (Voltage: 26V, Current: 250A).



(a) (b)

Figure 16. Field test of the mobile welding robot: (a) before moving longitudinal direction, (b) welding after moving longitudinal direction.

3.2.3.2 Motion generator module

The Action Module transfers the motion command to the motion generator module when the motion of the torch is necessary to perform tasks. The motion generator module generates the trajectory of the welding torch by using forward kinematics and inverse kinematics, and transfers the angle data of each motor to the servo module in the Task Executer.

3.2.4 Modules of the task executor

The modules of the Task Executer are the interface of hardware connected to the RRX3. The Task Executer controls the AC servo motor through USB communication with the motion controller. The Task Executer performs real-time communication (RS232, digital I/O) with the laser sensor, proximity sensor, and shock sensor, and transfers welding data (voltage and current) to the welding machine controller through RS485 communication. The Task Executer consists of the Servo Module, Sensor Module, Welding Machine Module, and the ON/OFF Module.

3.2.4.1 Servo module

The Servo Module transfers the angle data of each motor, calculated by the Motion Generator Module, to the motion controller, which controls the AC servo motor drivers. Communication between the Servo Module and the motion controller is performed via USB.

3.2.4.2 Sensor module

The Sensor Module transfers environmental data, which comes from the laser sensor, proximity sensor, and shock sensor via RS232 or digital I/O, to the Task Manager or to Actions for Task.

3.2.4.3 Welding machine module

The Welding Machine Module transfers welding data (voltage and current), provided by the Action Module, to the welding machine controller. The Welding Machine Module also receives the results of arc sensing from welding machine controller via RS485.

3.2.4.4 ON / OFF module

The ON/OFF Module performs non-periodic functions such as 'servo on/off' and 'open/close protection cap' of the laser sensor. Therefore, the ON/OFF Module merely waits for a signal from Action for Task. The ON/OFF Module performs its only function corresponding to the signal from Actions for Task, and after the required function has been completed, it reverts to the initial waiting state. The ON/OFF Module is necessary for the Laser Sensing Task because it opens and closes the protection cap of the laser sensor.

4. Implementation and experiment results

For robust control of the mobile welding robot, modules in the control software need to operate precisely within a given period. Therefore, QNX has been selected as the operating system based on its reliable real-time performance. The control software has been developed using C language. To verify the configuration of the hardware and to confirm the operation of the modularized control architecture, the transverse/longitudinal movement and welding tests have been performed. Figure 11 shows the test results.

4.1 Example of performing transverse moving task by combining modules

Figures 11(a), (b), (c), and (d) show the test results of the transverse movement to the right. As shown in Figure 12, the sequence of the transverse movement is as follows:

(1) The Action Module transfers the 'transverse movement' command to the servo module.
(2) The servo module transfers the 'lift body' command to the motion controller.
(3) After the body is lifted, the Servo Module transfers the 'move sub body right' command to the motion controller.
(4) The Sensor Module receives 'longi. detected' information and transfers it to the Action Module.
(5) The Action Module transfers the 'stop' command to the Servo Module. The Servo Module then stops the motors. Figure 11(b) shows the results of moving the sub body to the next longi.
(6) The Action Module operates the motors in sequence until RRX3 completes the transverse movement. The Sensor Module detects the longi and transfers the result to the Action Module, and the Action Module then transfers the 'stop' command to the Servo Module.

4.2 Example of performing longitudinal moving task by combining modules

(1) The Action Module transfers the 'longitudinal movement' command to the Servo Module.
(2) The Servo Module transfers the 'move forward' command to the motion controller.
(3) While RRX3 moves in the longitudinal direction, the Sensor Module receives the 'U-shaped areas detected' information from the laser sensor and transfers this information to the Action Module.
(4) The Action Module then transfers the 'stop' command to the Servo Module, and completes the longitudinal movement.

4.3 Example of performing the weaving welding task by combining modules

Figure 11(f) shows the welding result of the U-shaped welding areas. Weaving Welding refers to the vertical welding performed by the zigzag motion of the welding torch. As shown in Figure 13, the sequence of the Weaving Welding is as follows:

(1) The Motion Generator Module transfers the 'move welding torch from point A to point B' command to the Servo Module.
(2) The Servo Module transfers the 'start motors' command to the motion controller. The Welding Machine Module then transfers the 'start gathering welding current' command to the welding machine controller while the welding torch moves from Point A to Point B.
(3) The Servo Module waits for 0.3 seconds after the welding torch reaches Point B. Meanwhile, the welding machine controller checks if the welding torch successfully followed the required welding path using the compiled current data.
(4) The Motion Generator Module calculates the path of the welding torch from Point B to Point C based on the result of arc sensing.
(5) The Motion Generator Module transfers the calculated position of Point C to the Servo Module during the waiting time (0.3 seconds).
(6) Go to the second step after the waiting time (0.3 seconds).

Figure 14 shows the communication sequences of the modules in the Weaving Welding task. Consequently, RRX3 is able to detect the longi and moves in the transverse direction. In addition, the robot performs the welding task while sensing the welding points and following the welding path.

Figure 15 shows the welding results of the welding test for the mobile welding robot. To improve the welding quality, the input voltage and the current of the welding machine were adjusted several times. The results of one of the successful welding tests (26V and 250A) are shown in Figure 15. The test results confirm that the hardware is properly configured and the modularized control software architecture provides intended operation.

4.4 Results of field test

For the evaluating robustness of the developed embedded controller, the welding test was conducted in the shipyard for a month. Figure 16 shows that RRX3 is performing the mov-

Figure 17. Various types of welding targets that RRX3 successfully welds

ing tasks (Figure 16(a)), and welding tasks (Figure 16(b)).

Figure 17 shows that the various types of welding targets (U-shaped part). RRX3 moves to the welding targets and detects the welding seam, and successfully performed welding tasks several hundred times.

Compared with the existing system, DANDY, the field tests shows that the quality of welding using RRX3 is same as the quality of DANDY. Moreover, total sensing time to prepare the welding job was reduced about 25%. Since DANDY cannot deal with the welding of brackets on U-shaped parts, RRX3 can perform this welding job. Needless to say, it is more convenient that the worker did not need to move the welding device because of its functions for self-moving. Through this field test, we could confirm that the developed embedded controller of RRX3 is well designed and implemented.

5. Conclusions

This paper described a development of the embedded robot controller hardware and the control software for an autonomous mobile welding robot. The embedded controller and control software was applied to the autonomous mobile welding robot for successful execution of the following tasks: moving, welding, and sensing tasks. In order to develop an embedded type main controller, 12 AC servo motor drivers and a CPU board were installed in a limited space. For the modularizing architecture of control software, we designed control software with four layers: Task Manager, Task Planner, Actions for Task, and Task Executer. For evaluate this imbedded controller and control software, the field tests are conducted, it is confirmed that the developed embedded controller of RRX3 is well designed and implemented. Compared with the existing system, DANDY, RRX3 can reduce the heavy works for moving welding devices and the sensing time about 25% to prepare the welding job. We expect that this mobile welding robot can be utilized for the welding tasks in the double hull structure of shipyard.

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