applied sciences

MDPI

Article

The Developmentof Software to Automate the Laser Welding of a Liquefied Natural Gas Cargo Tank Using a Mobile Manipulator

Taeyong Choi [1,*], Jongwoo Park [1], Jeongae Bak [1], Dongil Park [1], Hyunuk Seo [1] and Sanghyun Kim [2]

1 Department of Robotics and Mechatronics, Korea Institute of Machinery and Materials, Daejeon 34103, Republic of Korea; jekiel@kimm.re.kr (J.P.); jabak@kimm.re.kr (J.B.); parkstar@kimm.re.kr (D.P.); shu@kimm.re.kr (H.S.)
2 Department of Mechanical Engineering, Kyung Hee University, Yongin-si 17104, Republic of Korea; kim87@khu.ac.kr
* Correspondence: taeyongc@kimm.re.kr

Abstract: The demand for liquefied natural gas (LNG) ships is increasing for various reasons. Despite their enormous size, cargo holds inside freighters transporting LNG have traditionally been constructed by welding to high-quality standards for safety. This process traditionally relies on manual labor or semi-automatic moving devices. In this study, a methodology was designed for robot-based automated laser welding inside large LNG cargo holds. The developed approach offers a practical solution to challenging issues such as the corrugation of the membrane that forms the inner walls of LNG cargo holds and the inter-floor movement of robots. This study analyzes and restructures the work for laser welding using mobile robots inside LNG cargo holds composed of membranes. For realistic constraints, such as inter-floor movement of robots and high-quality welding of membrane corrugations, methods integrated with manual work have been proposed. Additionally, for the overall membrane laser welding of the LNG cargo hold space, an automated method using robots was suggested. The developed methodology has been realized as operational software for the movement of robots for laser welding in LNG cargo holds.

Keywords: laser welding; mobile manipulator; LNG cargo hold; offline programming

check for updates

Citation: Choi, T.; Park, J.; Bak, J.; Park, D.; Seo, H.; Kim, S. The Development of Software to Automate the Laser Welding of a Liquefied Natural Gas Cargo Tank Using a Mobile Manipulator. *Appl. Sci.* **2024**, *14*, 134. https://doi.org/10.3390/app14010134

Academic Editor: Guijun Bi

Received: 13 November 2023
Revised: 7 December 2023
Accepted: 21 December 2023
Published: 22 December 2023

1. Introduction

Robotic technology plays a crucial role in various industries, particularly in the automotive sector, where it aids in the manufacturing process by improving production efficiency and enhancing product quality. By executing repetitive and precise tasks in automated operations, robots reduce production costs and enhance the safety of production lines. The use of robots in laser welding has been extensively researched due to its numerous advantages. Laser welding, which involves welding from a distance, has a reduced dependence on the shape of the object, making it an advantageous method for welding complex or angular objects. Furthermore, it offers the benefit of faster execution than conventional spot-welding methods as depicted in [1].

This study shifts the focus from the prevalent application of laser welding with robots in automobile manufacturing to the welding of LNG vessel cargo holds. The LNG cargo tank, a significant compartment found in LNG carriers, typically measures over 20 m in height, width, and depth, and may exceed 30 m in depth for specific vessels as shown in Figure 1. The inner surface of the LNG cargo tank is constructed through the welding of membrane modules, as depicted in Figure 2. The size and shape of the membranes vary based on their attachment location and specifications, and corrugations are incorporated into the membrane to accommodate temperature-induced volume fluctuations for safety during transport. Approximately 2000 membranes, each with dimensions of 3000 mm by 1000 mm, contribute to the construction of a single LNG cargo tank.

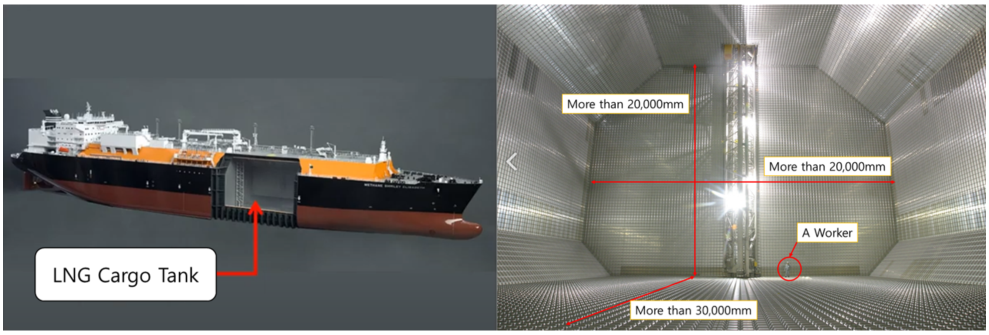

Figure 1. The left figure shows a general LNG ship. The right figure shows a LNG cargo tank. Generally, a ship has 4–6 tanks.

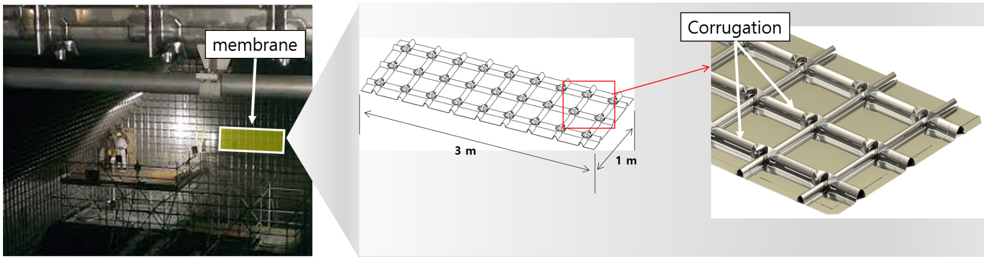

Figure 2. Membrane and corrugation consist of interior of LNG cargo tank.

The fabrication of an LNG cargo tank, due to its considerable size and intricacy, involves a labor-intensive process that requires much of the work to be performed manually. The production of a single LNG cargo tank can take several months to complete. Currently, the interior of the LNG cargo hold is welded together sequentially, similar to the construction of a building, using scaffolding to partition the floors and makeshift elevators to facilitate movement. The goal of this study is to increase automation by utilizing a mobile robot for laser welding throughout the entire process.

While prior research has explored offline programming methods for laser welding on complex objects [2,3], the application of offline programming software for mobile welding robots in the automation of expansive LNG cargo tank welding on a global scale has yet to be addressed. Ref. [4] utilized intelligent welding with robots through Virtual Reality technology, but the system relied on conventional fixed robotic systems and required frequent human intervention, rather than full automation. Similarly, ref. [5,6] conducted research on welding automation using vision sensors, but the resulting welding precision was lower than conventional methods and the application was limited to targets within a restricted working area of fixed robotic systems.

This research presents an autonomous laser welding approach for multi-layered structures, such as those found in LNG cargo holds, utilizing mobile robots to operate in expansive spaces. In order to achieve this goal, we have developed detailed welding procedures that can be executed by mobile robots, while also considering the limitations of complete automation. As such, the process has been divided into automated and manual components, with restrictions on the areas of the target that can be accessed. The welding process for LNG cargo holds utilizing mobile robots is programmed using the main offline programming (OLP) software, allowing for flexible application to a variety of task configurations.

2. Design of Robotic Laser Welding Process for LNG Cargo

2.1. Mobile Robot Configuration for Laser Welding

Until now, the successful implementation of laser welding using mobile robots has been elusive. The precision required for laser welding processes with mobile robots is inherently challenging, and there are limitations in outfitting mobile robots with the diverse array of devices necessary for laser welding. The welding head assembly employed in laser welding is notably heavy, necessitating robots with a payload capacity typically exceeding 20 kg. Additionally, power poses a limiting factor. A substantial power supply unit is indispensable to provide the required power for the mobile robot, the high-load robot arm, and the laser welding process, encompassing chiller power and laser light source power. Consequently, thick power cables, externally connected to each device with varying specifications, become essential. In laser welding, not only is a light source essential, but a chiller is also necessary for cooling. However, as the laser power increases, the volume of the chiller also expands, presenting challenges in integrating it into the mobile robot. Due to spatial constraints, significant enlargement of the mobile robot is impractical and, consequently, the chiller must be situated externally. The relatively large size of the robot arm controller further necessitates its external placement on the mobile robot.

Taking into account the various constraints, the mobile robot is equipped with a robot arm, its own controller, and a laser power supply device. The welding head assembly is attached to the robot arm, and other components such as the power supply device, chiller, and manipulator power are positioned externally on the mobile robot. As shown in Figure 3, this configuration integrates the welding process with the mobile robot system, optimizing space utilization and the efficiency of the welding process.

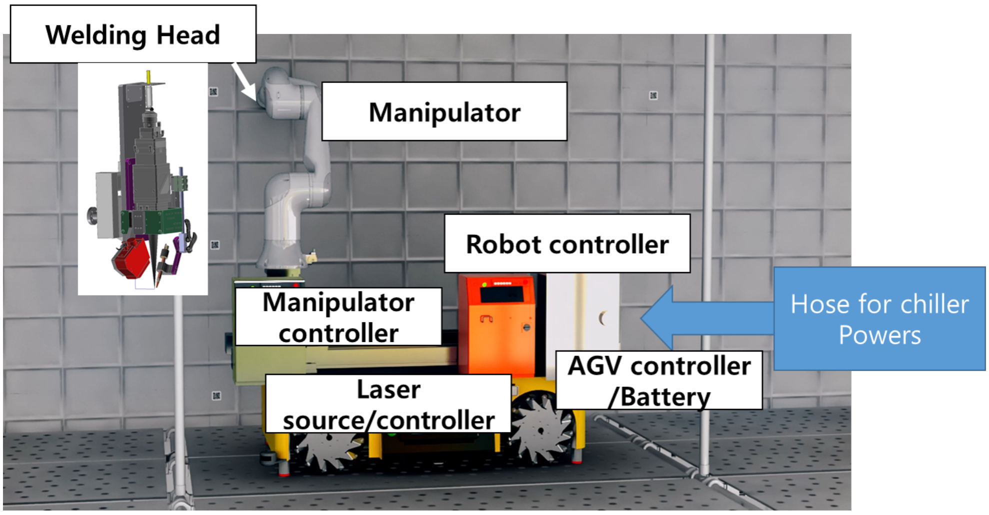

Figure 3. Mobile robot for laser welding consists of manipulator with laser welding assembly, robot controller, laser source, etc.

2.2. How to Secure the Precision of Mobile Robots

Precise positional movement of mobile robots in relation to the welding target is currently a challenging issue, particularly in expansive areas where minor errors in robot posture can lead to significant inaccuracies. To address this, it is crucial to accurately determine the initial position of the mobile robot. Many previous studies have explored mobile robot navigation, such as [7,8]. In this study, an omni-directional wheel was used to achieve flexible motion in a narrow space. Although omni-directional wheels have been extensively studied as described in [9], their mechanical limitations make it difficult to achieve precise movement. To correct the position error of the mobile robot, a one-degree-of-freedom slide was added to the end welding head. This approach is different from conventional stationary laser-welding robots, where high positional accuracy is achieved through pre-workspace calibration. Instead, the aim of this study is to overcome position errors arising from movement and seam tracking errors through end-effector correction actions.

To address the issue of determining the position and orientation of a mobile robot in complex indoor environments, QR codes are utilized. The robot analyzes the distortion of the QR codes within its field of view and adjusts its orientation accordingly to estimate and correct its position and orientation errors. Conventional image recognition methods may not be sufficient in such environments, and installing additional devices for high-cost indoor positioning is not practical in vast open spaces such as LNG cargo bays. In challenging conditions where installation of network devices and additional equipment is difficult, QR code-based location recognition provides a cost-effective and efficient solution for explicit robot position identification, including position correction. This method is particularly useful in situations with complex environments, such as those encountered in LNG cargo bays.

The movement of the robot is also a challenging aspect, particularly in the case of LNG cargo tanks where the ground environment is comparable to outdoor conditions, making it difficult for the robot to move in a straight line at a consistent speed, which is essential not only for precise positioning, but also for achieving high-quality welding, as planned. There are no large robots available for laser welding within vast LNG cargo holds that are capable of movement between different levels. Although studies such as [10–12] have been conducted on robots with elevator-like movements for logistics and transportation purposes, laser welding robots face the challenge of accommodating very thick cables due to issues such as wiring, cooling, and power requirements. Technical and procedural solutions are required to address these issues.

2.3. Overview of LNG Cargo Hold Welding Procedure Using Mobile Robot

The automation of the entire LNG cargo-hold laser welding process is currently hindered by technological limitations. To overcome this, we have devised a robot-based laser welding procedure that is divided into segments that can be automated and those that require human intervention. The LNG cargo holds typically consist of 7–8 layers, and inter-floor movement is facilitated by remote control of robots navigating elevators. Even in traditional manual operations, a heavy-duty elevator with a capacity of approximately 1 ton is installed for equipment transfer. In the working environment of LNG cargo bays, various cables, including laser wires, power cables, and water tubes for chillers, required for laser welding, are pre-positioned on each floor and connected to the robot using reels. Upon reaching the target floor, the robot connects the necessary cables using reels and then moves to its initial position. To address the challenges associated with the mobility of the robot, a one-degree-of-freedom scanner of [13] was attached to the robot end effector to reduce positional errors in confined spaces. The welding procedure for the robot operation was established as follows:

1. The mobile robot moved to the initial position of the target layer. To minimize possible positional errors, markers, such as QR codes, were pre-installed on the membrane.
2. In a stationary state, the robot identifies weldable seams on the membrane considering the robot's working area. The pre-installed information about the membrane is stored in a database (DB) format and includes the path information for the left, right, bottom, and top lines of the membrane.
3. The welding sequence for the identified weldable seams was determined by considering factors such as overlapping areas between membranes, constraints such as one-time operations considering the characteristics of welding, and other limiting conditions.
4. The robot moves to the next pre-planned stopping position, and Steps 2 and 3 are repeated. The stopping positions for the robot movement are preset, considering the robot's working area and safety margins. Precision markers were installed at stopping positions.

Once the task for a specific layer has been completed, the robot will move to the next layer. This movement was facilitated manually. Initially, the thick power cables and coolant lines attached to the robot were disconnected. Subsequently, the robot arm was remotely folded using a control system, allowing the robot to move through a relatively narrow elevator. An elevator was then utilized to transport the robot to the next floor, where the robot cable bundle was reinstalled. The subsequent steps were identical to those described in Step 1.

As previously stated, an advanced software program has been developed to streamline the welding process for LNG cargo bays. This software employs robots in the work area equipped with laser welding capabilities and offers real-time monitoring and control of the work status. Furthermore, it utilizes a pre-configured Membrane DB to generate precise robot movements.

3. Development of a Software for LNG Cargo Welding Automation Using Mobile Robots

3.1. Fundamental Functions of the Developed Software

The developed software distinguishes itself from existing offline programming commercial software, such as [14,15], by its compatibility with mobile manipulators and its ability to handle large workspaces, including intricate tasks that involve both movement and welding operations.

The software comprises two primary components: one that processes spatial information related to the LNG cargo window, and the other that generates robot movements based on identified topology information. The overall architecture of the software is depicted in Figure 4. There are two methods for determining the spatial information of the LNG cargo window: extracting topology information between membranes that form the window from CAD files, or receiving input in the form of a self-generated Topology Description File (TDF). If the input is in the form of CAD, the topology generator simultaneously generates TDF files and internal memory space using the extracted topology information. These inputs are illustrated in Figure 4a,b.

Figure 5 illustrates the topology of the LNG cargo window. The composition of the LNG cargo window comprises membranes, the topology of which is determined by specifying the names of the membranes located above, below, to the left, and to the right of each membrane. The Topology Definition File (TDF) lists the topology information of all membranes constituting the LNG cargo window, where the topology information of each membrane is expressed by the unique membrane names surrounding it in all directions. The first field of topology information, the membrane name, represents the unique name of the membrane, while the second field, the membrane type, indicates the type of membrane. The LNG cargo window has been created by combining various types of membranes.

It is mandatory to adhere to certain guidelines when extracting topology information from CAD files, particularly in the case of a multilayered LNG cargo window, wherein a solitary layer must be assembled and the entire LNG cargo window assembly must be depicted as a collection of assemblies demarcated by layers. Each layer comprises a horizontal enumeration of the membrane component parts that make up that layer. In this context, the names of membrane components must be unique. In the program developed, the membranes were identified by their names without an additional identifier. For example, the names of the membranes are utilized to represent the relative arrangement of the membranes in TDF.

It is imperative to comprehend the spatial information of the LNG cargo window before generating robot movements for membrane-joining. Although the robot has general autonomous driving capabilities, the mixed-use function of layer-by-layer maps due to inter-floor movement has not been implemented. However, separate maps have been developed for each destination floor, allowing users to input the current floor and enable autonomous driving on that floor.

For welding tasks, the robot must identify the weldable area from its current position. This function is unnecessary for typical stationary robots, but is crucial for robot welding while moving through vast spaces. The weldable area includes not only spatial coordinates, but also the recognition of the membranes included in that area. The robot engages in laser welding considering the quality of the welding, and the target seam must be welded in a single operation. In an LNG cargo window composed of membranes, the welding target seam is ultimately one of the four directions of the membrane edge. Therefore, the membrane completely belonging to the manipulator's operational area of the mobile robot is defined as the Membrane Of Interest (MOI), as represented by (e) in Figure 4. In reality, MOI includes approximately one to three membranes from a single membrane, considering the size of the membranes and support load of the elevator and scaffold in the LNG cargo window space.

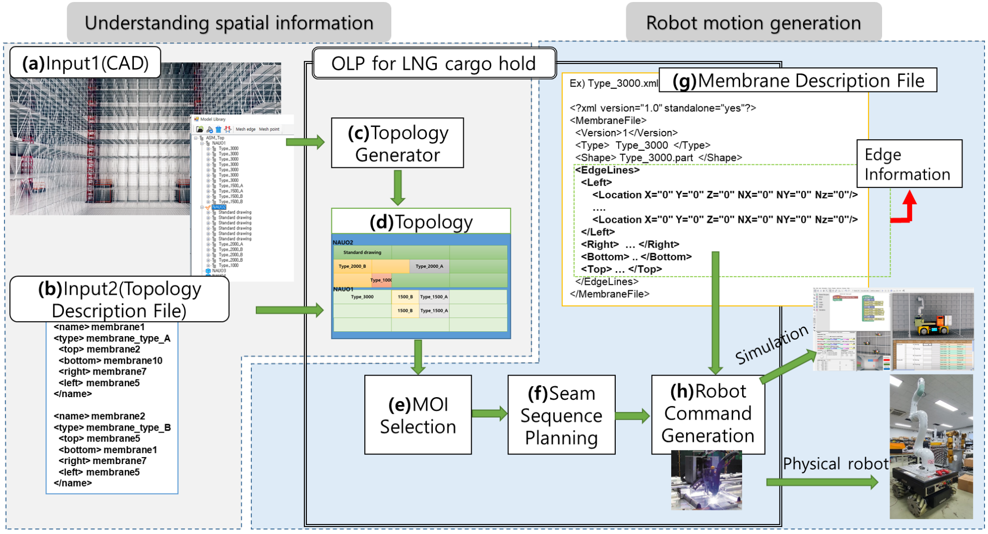

Figure 4. Designed software structure for LNG cargo laser welding process automation.

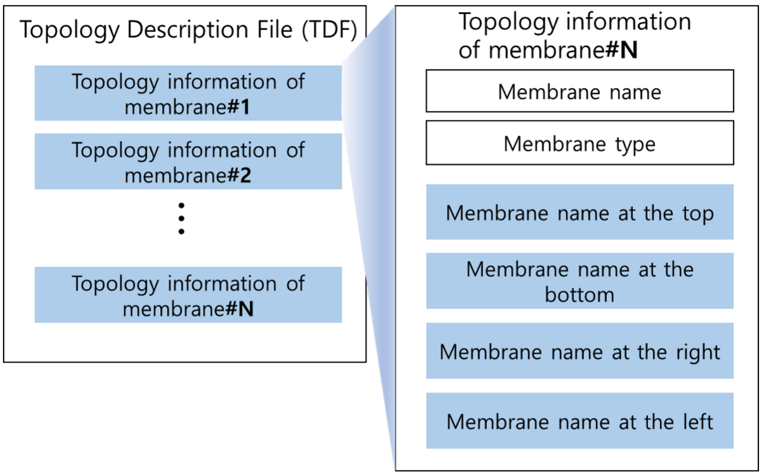

Figure 5. Topology description file to express the mutual positions between membranes.

Once the MOI was set, it was necessary to determine the actual seam for laser welding, as represented by (f) in Figure 4. In conventional laser welding using robots, the seam has a continuous trajectory; however, in this development, it is expressed as a sequential arrangement of membrane edges. This is because actual welding involves overlapping welding between the membrane edges. Thus, among the two overlapped membrane edges, that above is the welding target. Generally, the lower membrane among the overlapped membranes in the vertical direction and the left membrane among the overlapped membranes in the horizontal direction were considered, although the opposite was also possible. While it is possible to arbitrarily determine the order by considering only the robot's workspace without considering the quality of welding, in practice, the order is typically determined based on field expertise considering welding quality. It is essential to note that laser welding of the internal membranes of the target LNG cargo window was previously performed by humans, and various techniques for high-quality welding have been developed. This development software does not consider separate methods for improving the welding quality, aiming to capture the actions of human operators as much as possible to maintain the quality of welding.

Through the preceding process, the target and sequence for robot welding were determined. However, the trajectory of the welding target seam was not considered in the previous steps, and it was addressed in the (h) robot command generation step shown in Figure 4. For the specific generation of robot trajectories, the development software defines the (e) Membrane Description File (MDF). Figure 6 illustrates the concept of MDF. MDF has the membrane type as the first field and the membrane shape as the second field. The membrane shape provides information about the CAD file for the 3D simulation. The most crucial part of MDF is the edge information section. Every membrane has top, bottom, left, and right edges; for each edge, the actual robot-assisted laser welding method is included in the edge information. Edge information can contain two types of data: the trajectory information of the edge for robot simulation and the robot command set for the actual welding operation. To achieve high-quality welding, the motion of the robot arm, synchronized laser intensity, and angles are crucial, as determined through the preliminary experiments. The welding method and procedure for all edges in all directions were predetermined based on the membrane type. The development program outputs the preset robot system operation in sequential order according to the determined seam-welding sequence in Figure 4f. In the simulation, the simulated robot follows the sequentially arranged robot trajectory, allowing confirmation of the robot's movement and posture, but does not account for the welding quality.

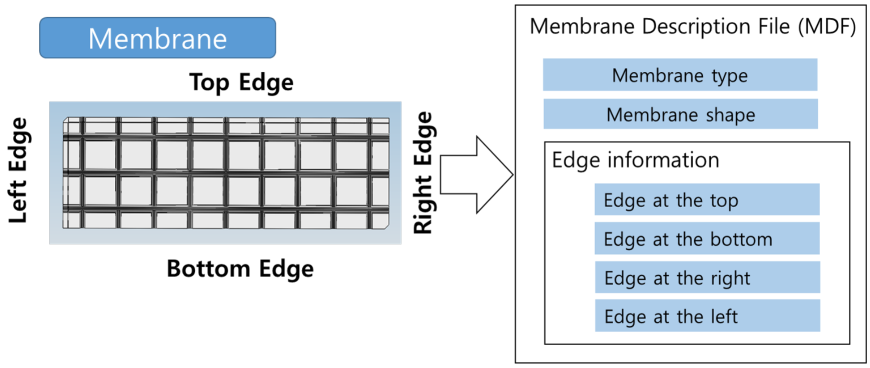

Figure 6. Membrane description file format for expressing information about membrane objects.

3.2. How to Ensure Seam-Tracking Precision

As previously mentioned, a commercially available seam-tracking device with a single degree of freedom was used as the baseline. While it ensures reliability in laser welding, it has limitations in terms of the operational range. Depending on the manufacturing specifications, it can roughly achieve a linear movement of 100 mm along one axis. Therefore, as long as the positional error of the robot end effector concerning the welding line falls within the operational range, welding can proceed without issues.

However, in this study, the extensive workspace of the robot led to significant positional errors even with small rotational discrepancies at the end effector. To address this issue, seam-tracking errors were periodically monitored, and corrective measures were taken in the pose of the robot when there was a substantial positional error between the target welding line and the robot's final end effector. Specifically, a dual-control routine structure was employed, as depicted in Figure 7, consisting of an external control routine with a low control cycle that corrects the position of the robot's end effector. Simultaneously, a high-speed control routine is designed to govern the end-effector device of the welding head. The low-frequency external control routine, shown in Figure 7 as (a), (b), (d), generates a corrected end effector position command, $\tilde{p}$, addressing the end effector position error without considering the welding head. Meanwhile, the high-speed control routine, composed of (d) and (e), generates real-time correction drive commands Δp_w for the seam-tracker. w_s represents the sensing values recognized by the commercial seam tracker.

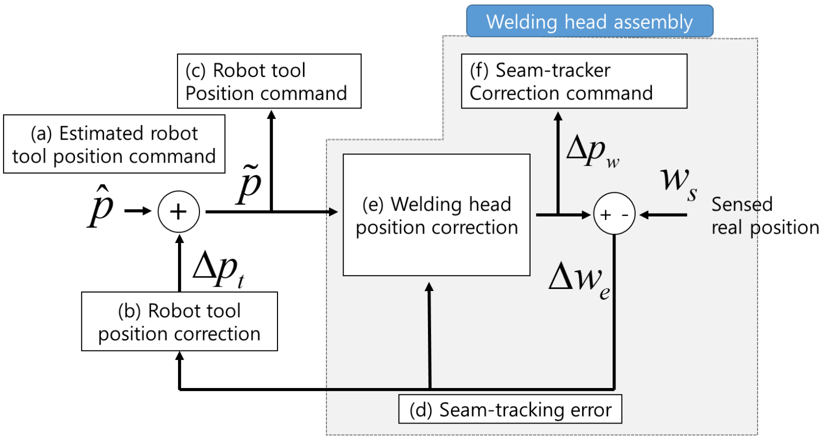

Figure 7. Dual control loop for seam-tracking error correction.

When employing robotic laser welding in LNG cargo holds, the considerable size of the holds poses a significant mobility challenge. Simultaneously, specific issues within the laser welding process must be addressed, particularly those concerning LNG tanks equipped with membranes. The membrane served as a unit module comprising the inner walls of the LNG cargo. Although the membrane dimensions may vary, the most commonly utilized size is approximately 3000 mm in width and 1000 mm in height. Given the explosive risks associated with LNG cargo holds, the laser welding quality is of paramount importance. Achieving welding of one side of the membrane in a single pass is essential for safety. This necessitates a robot capable of laser welding a 3000 mm long profile in one uninterrupted operation, requiring a robot arm with a working range exceeding 3000 mm.

The membrane incorporates special corrugations designed to accommodate the volume expansion resulting from the elevated temperature of LNG gas. These corrugations pose substantial challenges for robot-based laser welding owing to their pronounced curvatures. In conventional straight-line laser welding, the robot maintains a constant speed and adjusts the wire feed rate, laser intensity, and robot travel speed accordingly. However, determining process variables, such as wire feed speed, quantity, laser intensity, and robot travel speed for corrugations, is intricate and often involves extensive experimentation.

Owing to the high curvature of the corrugations, the robot faces challenges in maintaining a constant speed along the path, and there is a possibility of collision owing to the size of the laser-welding head. Adapting to changes in the robot's path profile requires complex and crucial adjustments to parameters, such as the wire feed rate and laser intensity. Figure 8 illustrates the configuration of the robot end effector device welding the corrugations of the membrane, consisting of (a) wire feeder, (b) laser, and (c) vision sensor. The angle (d) formed between the robot end effector and the membrane wall at the beginning and end of the corrugation decreases as the corrugation progresses, increasing the likelihood of collision with (c) the vision sensor and wall. (b) The laser was depicted as a conical object in the simulation. In an ideal scenario, the laser achieves the highest welding quality when perpendicular to the seam, considering that the laser in the development is simulated as an idealized cone-shaped object.

In this development, the actual robot did not generate welding paths that directly considered corrugations. Building on previous process studies, the development software assumes the pre-existence of robot and welding head movements suitable for laser welding considering corrugations. Utilizing these robot movements as the basic components, this study proposes a method for welding extensive LNG cargo compartments using a mobile robot.

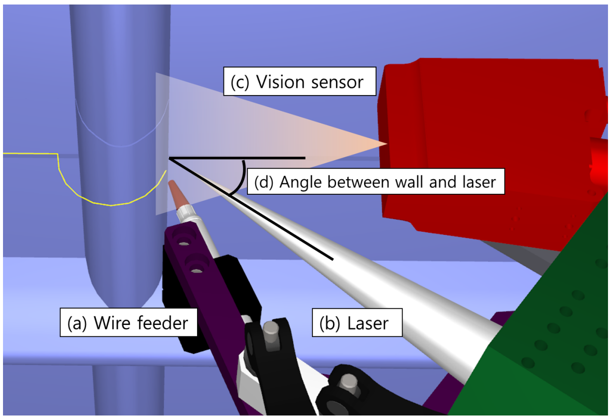

Figure 8. Space problem between robot end and wall during corrugation laser welding.

4. Simulation Studies

The operation of the developed software was validated through simulations. The mobile robot utilized in the simulations consisted of three components: mobile base, manipulator, and welding head. Each component is assumed to use products with established operability and no control-related issues are anticipated. It was assumed that the robot accurately followed the commanded robot motion instructions.

Simulation validation encompasses two main aspects. First, it verifies the understanding of spatial information, as illustrated in the space information comprehension section of Figure 4. Second, it validates the generation of robot motions.

4.1. Recognition of Membrane-Based Wall

The developed software verified the understanding of spatial information in the LNG cargo hold composed of membranes, as shown in Figure 5. The analysis focused on a two-tiered wall, as depicted in Figure 9, with each tier constructed with various membranes, as illustrated in Figure 10. The '(a) Main software' in Figure 9 visualizes the loaded environment and internally maintains separate models for the environment and the robot. The '(b) Model library' shown in Figure 9 recognizes the membranes composing the entire two-tiered environment model, as displayed in (f). It separates and identifies each tier, lists the membranes comprising each tier, and allows inspection of the MDF for an individual membrane, as shown in (e). The robot model employs a laser-weldable model with a maximum reach of 1808 mm and, consequently, the MOI at the defined stop position (d) is understood, as depicted in (c). Specifically, it corresponds to the red portion in Figure 10. To enhance the quality of laser welding, membranes capable of simultaneous welding operations were set as MOIs, and only five membranes within the dashed area were included, as indicated for optimization.

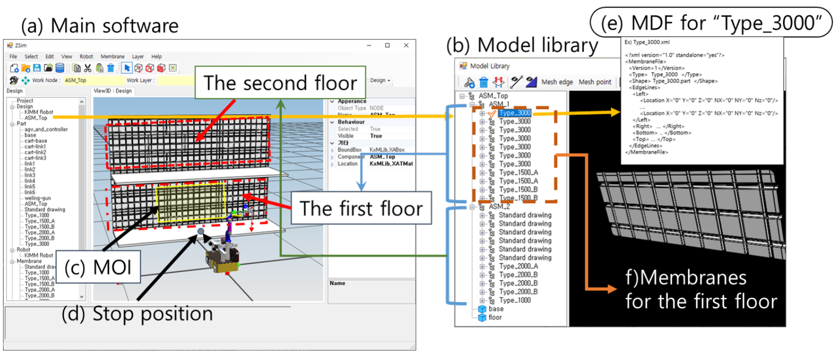

Figure 9. The developed program can obtain information about the membrane that makes up the LNG cargo hold from a given CAD file.

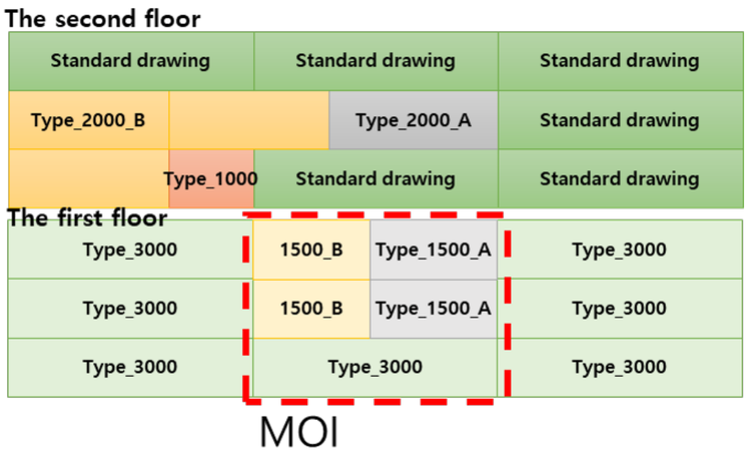

Figure 10. Membrane configuration forming a two-layer sample environment.

4.2. Robot Motion for Membrane Laser Welding

As mentioned earlier, discrepancies such as position and velocity errors between the simulation and the actual robot were addressed through a dedicated calibration algorithm. Therefore, validating the operation of the developed software through simulations is important.

To validate the robot motions, a physical implementation was conducted in a scaled-down demo environment of the large LNG cargo hold being produced, as shown in Figure 11. Although Figure 11 consists of a single layer, simulation verification of robot motions is adequate, as inter-layer movement in this development is manually controlled by the operator. The working space, which is composed of membranes, has a height of 3400 mm and is structured with three membranes.

The robot model features a mobile robot with a 6-DOF manipulator mounted on top. To secure the workspace both above and below, a vertical movement axis was added to the mobile robot. The mobile robot has dimensions of 1200 mm in width and 600 mm in height, and an additional vertical stroke of 500 mm. The manipulator used for welding is the same as that described in Section 4.1, with a maximum reach of 1808 mm. While the actual model is an industrial robot with a payload capacity of 35 kg, the payload is irrelevant in the simulation because the dynamics are not considered.

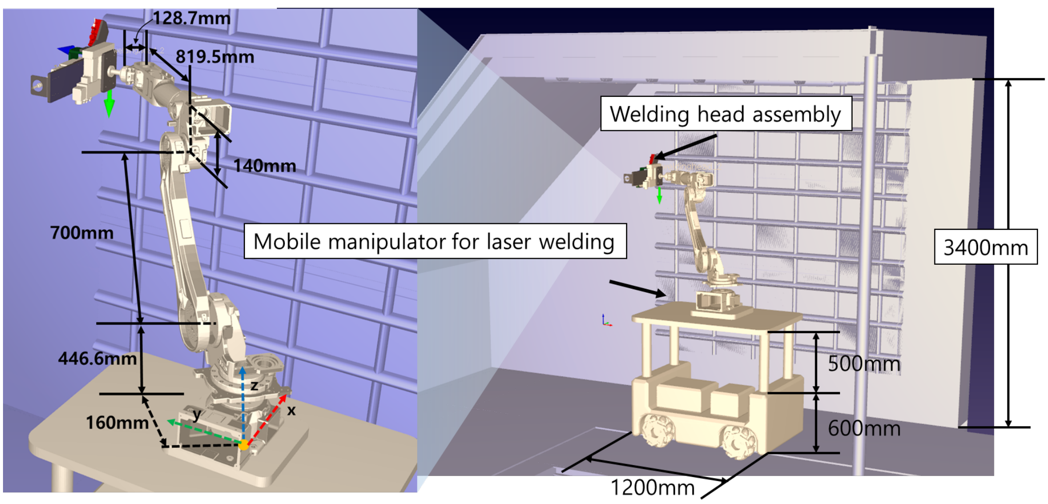

Figure 11. Simulation configuration: 1 layer of LNG cargo with laser welding mobile manipulator.

The membranes targeted for welding by the robot are shown in Figure 12. The model has dimensions of 2500 mm in width and 950 mm in height, with six corrugations on the top and bottom edges and three on the right and left edges. As illustrated in Figure 12, the characteristic feature of the corrugation path is a symmetrical conical shape consisting of three sections, S1, S2, and S3, each with different curvatures. S1, S2, and S3 represent round shapes with various curvatures. Simulation confirms the ability to trace the path; however, actual robot motions considering welding quality through integration with the welding device need to be validated through process research on actual membranes. Although the detailed robot motions may differ through the study of laser welding processes, simulation-based seam tracking allows for macroscopic verification of robot and environment collisions and confirmation of robot motion range and speed during membrane welding considering corrugations.

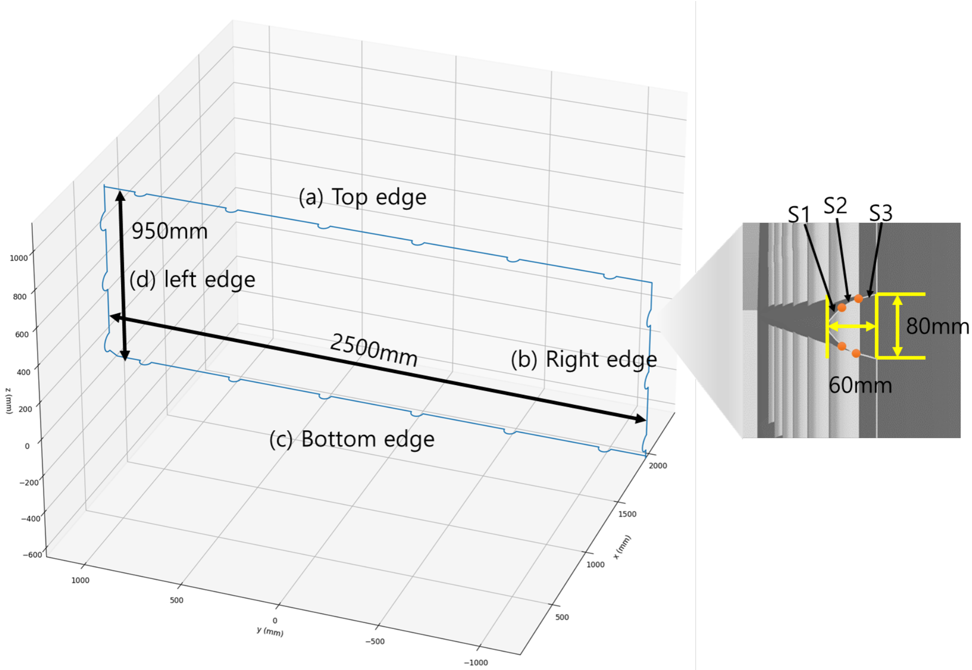

Figure 12. Membrane and corrugation configuration used in simulation.

The seam-tracking sequence was determined as shown in Figure 13. When numbering the three membranes in the sample process from bottom to top, as shown in (1), (2), and (3), the welding sequence is a straightforward sequential welding from bottom to top. In overlapping sections, where membranes (1) and (2) overlap and (2) and (3) overlap, the top edge of the lower membrane slightly overlaps the bottom edge of the upper membrane.

The simulation of the robot's motion in welding the lowest membrane of the three is depicted in Figure 14. The sequence followed was the top, right, bottom, and left edges. As the membrane was positioned at a lower level, the vertical linear drive axis of the mobile robot was in its home position. The angles and angular velocities of the six joints of the manipulator are shown in Figure 15 and Figure 16, respectively. These figures confirm the suitability of the robot's joint motion range and speed range for the intended task, when compared to the industrial robot intended for use. In particular, the corrugation section, which requires an extensive joint motion range and abrupt speed, falls within the normal operating range of the robot.

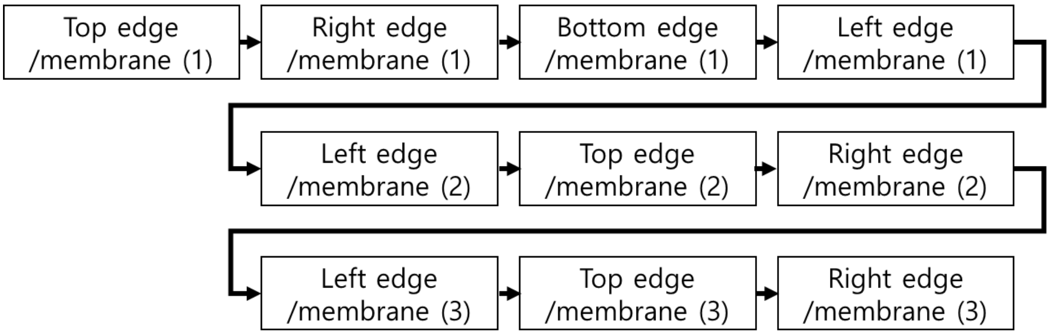

Figure 13. Seam welding sequence for the designed environment.

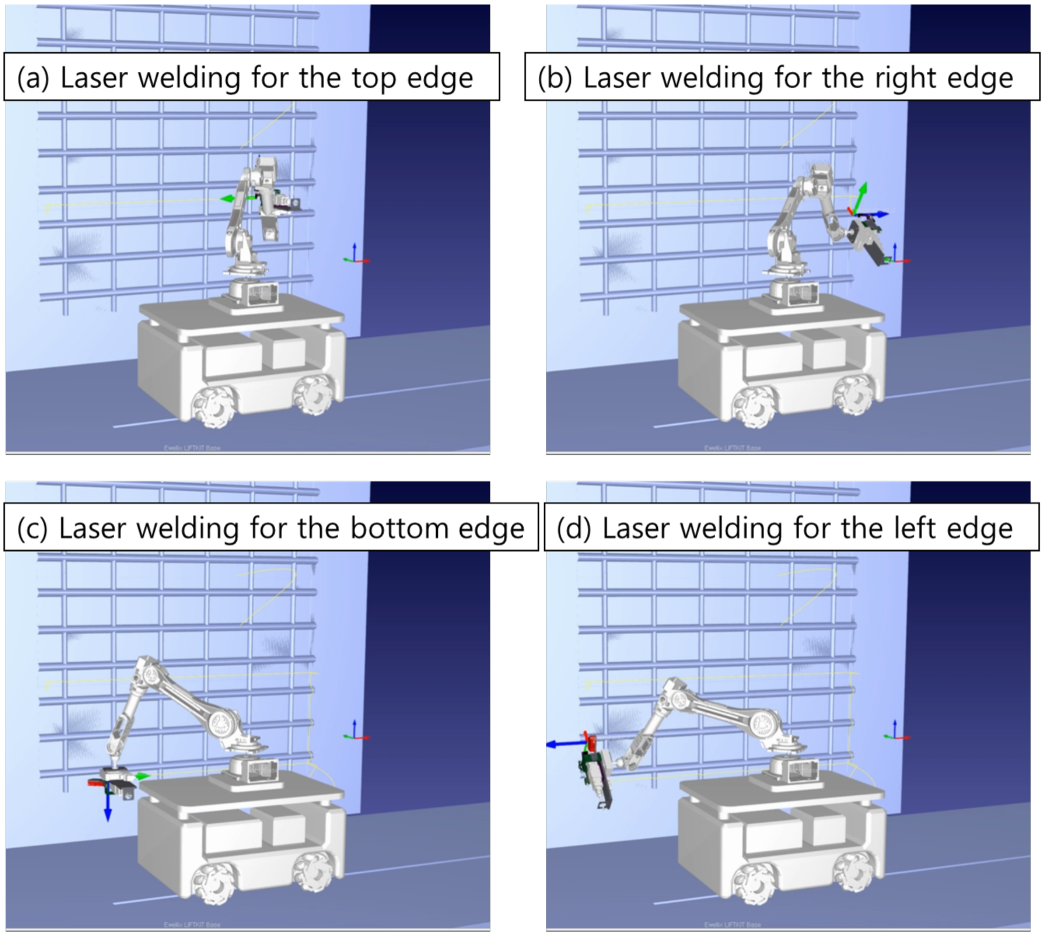

Figure 14. The order in which the mobile robot laser welds the membrane and the operating posture at each edge.

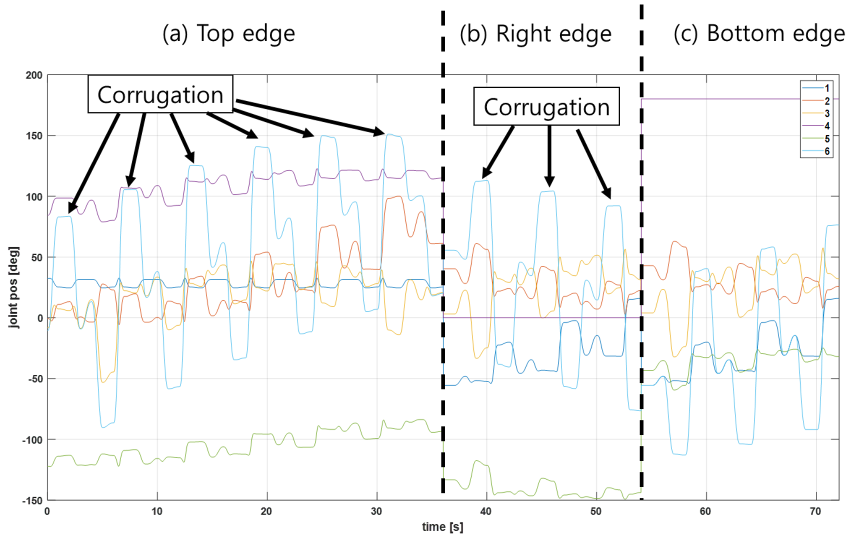

Figure 15. Joint angle values of each manipulator joint when welding a membrane. The numbers in the legend are the joint indices of the manipulator, starting with 1 from the base and the index of the last joint is 6.

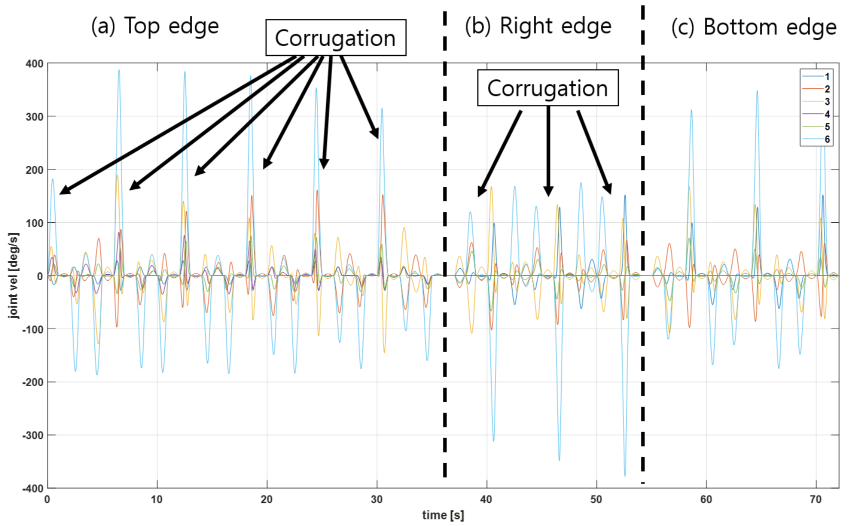

Figure 16. Joint velocity values of each manipulator joint when welding a membrane. The numbers in the legend are the joint indices of the manipulator, starting with 1 from the base and the index of the last joint is 6.

4.3. Generation of Membrane Weld Path

In the case illustrated in Figure 11, as previously explained, when the robot is positioned at predefined locations, the welding sequence for edges, as determined in Figure 13, is established. The robot's motion path is generated using this Edge information. Predefined robot actions in the Edge information of the MDF are based on path points for the '(a) teaching membrane in Figure 17, where a human operator initially performed the welding task. In other words, when the robot welds the teaching membrane, it follows the Edge information in the MDF, replicating the actions taught.

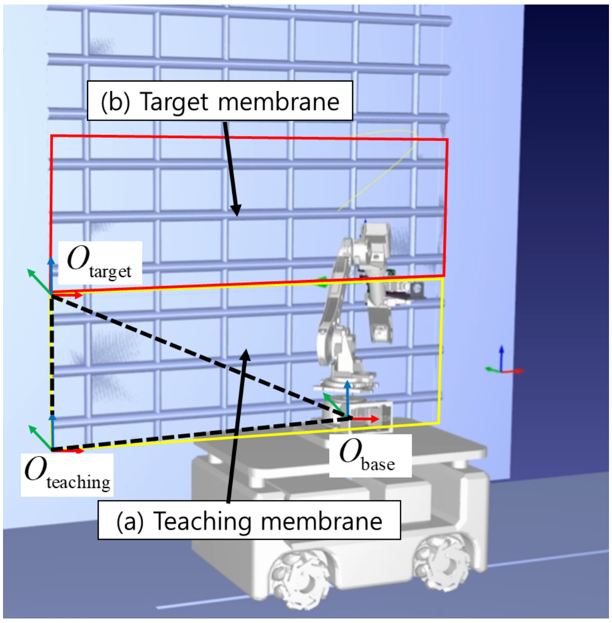

Figure 17. Coordination relations among membranes and robot.

When welding a non-reference membrane, the coordinates of the path points in the MDF's Edge information are adjusted based on the relative positional relationship between the reference membrane and the target membrane. The relative positional relationship with the reference membrane is determined based on the topology information of the LNG cargo hold. Since the membrane's size is a known value, the 2D relative position on the plane can be easily determined using the relative location from the reference membrane to the target membrane, utilizing the known sizes.

Let us denote the robot's reference coordinate system as O_{base}, the teaching membrane's reference coordinate system as $O_{teaching}$, and the target membrane's reference coordinate system as O_{target}. Each is depicted in Figure 17.

$$P_{\text{teaching}}|_{O_{\text{base}}} = \{p_1, p_2, \cdots, p_n\}|_{O_{\text{base}}} \tag{1}$$

$$P_{\text{teaching}}|_{O_{\text{teaching}}} = T^{\text{teaching}}_{\text{base}}(P_{\text{teaching}}|_{O_{\text{base}}}) \tag{2}$$

The Edge information for the teaching membrane is constructed based on the initial teaching points in O_{base} during the first teaching session, as represented in (1). In (1), $p_1, p_2, \cdots, p_n$ represent each teaching point.

To perform robot welding on the target membrane in O_{target}, the teaching points in (1) must be expressed in the coordinate system of O_{target}. To achieve this, the teaching points are first transformed using (2) to $O_{teaching}$ coordinates. When defining the teaching points in $O_{teaching}$ as in (3), it must match (4). This relationship is expressed in (5). The remaining step is to express (4) in the robot's reference coordinate system O_{base}, which can be achieved using a simple homogeneous transform function in (6). In (6), $T^{\text{teaching}}_{\text{target}}$ moves the points from O_{target} to $O_{teaching}$, and $T^{\text{base}}_{\text{teaching}}$ moves the points from $O_{teaching}$ to O_{base}. In the case of Figure 17, the relationship between *(a) teaching membrane* and *(b) target membrane* involves a simple upward horizontal shift, reflected in $T^{\text{teaching}}_{\text{target}}$.

$$P_{\text{teaching}}|_{O_{\text{teaching}}} = \{p'_1, p'_2, \cdots, p'_n\}|_{O_{\text{teaching}}} \tag{3}$$

$$P_{\text{target}}|_{O_{\text{target}}} = \{p'_1, p'_2, \cdots, p'_n\}|_{O_{\text{target}}} \tag{4}$$

$$P_{\text{teaching}}|_{O_{\text{teaching}}} = P_{\text{target}}|_{O_{\text{target}}} \tag{5}$$

$$T^{\text{base}}_{\text{target}} = T^{\text{base}}_{\text{teaching}} T^{\text{teaching}}_{\text{target}} \tag{6}$$

5. Discussion

5.1. Independence of the Development Program from Actual Robot Behavior

In summary, the program developed has the capability to read the spatial information of the LNG cargo hold and then reproduce robot movements for welding a single membrane at an arbitrary position. However, if there are multiple types of membranes, the program must have pre-secured robot movements for welding each type of membrane. When reproducing robot movements at an arbitrary position, the program will replicate the pre-secured robot welding movements based on the type of membrane.

Accordingly, the functionality of the program developed is separate from the actual operations of the robot and is suitable for simulation purposes only. The practical application of a robot and related equipment for membrane welding is a complex area of research in its own right. At present, it largely depends on human expertise, which makes automation challenging. The quality of laser welding for membranes is not solely determined by the robot's movements and welding head, but is also influenced by factors such as the laser's wavelength, intensity, focus, and wire supply.

5.2. Space Limitations for Application of Developed Technology to LNG Cargo Holds

A real LNG cargo tank is a large and complex three-dimensional space, as shown in Figure 1. There is basically a floor and a ceiling, and due to the complexity of the shape, there are many corners where faces meet. Robots designed to weld on vertical walls have a hard time working on floors and ceilings due to the limitations of their range of motion. Of course, it is possible to increase the working area by adding additional joints, but this introduces additional problems such as vibration and magnetic collisions during the robot's work. Furthermore, as mentioned in the introduction, there is the fundamental problem of overstretching the size and weight of the robot, which is limited for floor maneuvering.

The problem becomes more intricate when considering the edges, as human operators currently manually weld multiple membranes with arbitrary shapes to join them. In order to automate such tasks with robots, the workflow must be systematized to be programmable. However, at present, the tasks are determined arbitrarily based on the judgment of human operators. Furthermore, the edge region presents a fundamental challenge of severely restricted robot workspace due to the potential for collisions between the robot's welding head and the surrounding environment. For these reasons, the proposed approach limits the robotic welding focus to the vertical walls of a two-dimensional plane.

6. Conclusions

In this study, a methodology for laser welding using mobile robots in large environments, such as LNG cargo holds, was designed and implemented using software. To achieve this, we first identified realistic constraints for the application of robots in vast environments such as LNG cargo holds. The system was divided into robotic and non-robotic components. For the inter-floor movement of mobile robots, we designed a manual procedure involving cable detachment and elevator-assisted floor transitions, followed by the reconnection and resumption of automated procedures. For a single floor, we developed software that enables welding operations using mobile robots. Notably, we designed and implemented a robotic-based automated method based on welding templates for membrane-edge welding, considering the laser welding quality of the membranes composing the interior of LNG cargo holds. The functionality of the developed software was validated through simulations.

We are currently engaged in the active operation and experimentation of robots. However, the primary objective of this investigation is not to concentrate on the robot itself, but rather on the methodology of utilizing mobile robots in multiple-tiered environments, such as the cargo holds of LNG carriers, for laser welding. The proposed methodologies and algorithms were validated through simulations. Although it is anticipated that the proposed methodology will undergo further refinement through actual robot operations and experiments in the future, this will be the subject of future research endeavors.

Author Contributions: The contributions of the authors of this work are as follows: Conceptualization, T.C., J.P. and D.P.; methodology, J.P. and T.C.; software, J.P. and S.K.; validation, J.B., H.S. and T.C.; formal analysis, T.C.; investigation, T.C. and J.P.; writing—original draft preparation, T.C.; writing—review and editing, J.P., D.P. and J.B.; visualization, T.C. and S.K.; supervision, T.C.; project administration, T.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Technology Innovation Program (No. 20014923) funded by the Ministry of Trade, Industry and Energy, Korea Government.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

LNG	Liquefied Natural Gas
OLP	Off-Line Programming
MOI	Membranes Of Interest
TDF	Topology Description File
MDF	Membrane Description File

References

1. Erdős, G.; Kardos, C.; Kemény, Z.; Kovács, A.; Váncza, J. Process planning and offline programming for robotic remote laser welding systems. *Int. J. Comput. Integr. Manuf.* **2016**, *29*, 1287–1306. [CrossRef]
2. Polden, J.; Pan, Z.; Larkin, N.; Duin, S.V.; Norrish, J. Offline programming for a complex welding system using DELMIA automation. In *Robotic Welding, Intelligence and Automation*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 341–349.
3. Nägele, L.; Macho, M.; Angerer, A.; Hoffmann, A.; Vistein, M.; Schönheits, M.; Reif, W. A backward-oriented approach for offline programming of complex manufacturing tasks. In Proceedings of the 2015 6th International Conference on Automation, Robotics and Applications (ICARA), Queenstown, New Zealand, 17–19 February 2015; IEEE: Piscataway, NJ, USA, 2015; pp. 124–130.
4. Su, Y.P.; Chen, X.Q.; Zhou, T.; Pretty, C.; Chase, G. Mixed reality-enhanced intuitive teleoperation with hybrid virtual fixtures for intelligent robotic welding. *Appl. Sci.* **2021**, *11*, 11280. [CrossRef]
5. Ciszak, O.; Juszkiewicz, J.; Suszyński, M. Programming of industrial robots using the recognition of geometric signs in flexible welding process. *Symmetry* **2020**, *12*, 1429. [CrossRef]
6. Zhang, G.; Huang, J.; Wu, Y.; Yang, G.; Di, S.; Yuan, H.; Cao, X.; Shin, K. A Novel 3D Complex Welding Seam Tracking Method in Symmetrical Robotic MAG Welding Process Using a Laser Vision Sensing. *Symmetry* **2023**, *15*, 1093. [CrossRef]
7. Xiao, X.; Liu, B.; Warnell, G.; Stone, P. Motion planning and control for mobile robot navigation using machine learning: A survey. *Auton. Robot.* **2022**, *46*, 569–597. [CrossRef]
8. Raj, R.; Kos, A. A comprehensive study of mobile robot: History, developments, applications, and future research perspectives. *Appl. Sci.* **2022**, *12*, 6951. [CrossRef]
9. Popovici, A.T.; Dosoftei, C.C.; Budaciu, C. Kinematics Calibration and Validation Approach Using Indoor Positioning System for an Omnidirectional Mobile Robot. *Sensors* **2022**, *22*, 8590. [CrossRef] [PubMed]
10. Palacín, J.; Bitriá, R.; Rubies, E.; Clotet, E. A Procedure for Taking a Remotely Controlled Elevator with an Autonomous Mobile Robot Based on 2D LIDAR. *Sensors* **2023**, *23*, 6089. [CrossRef] [PubMed]
11. Zhao, J.; Chen, Y.; Lou, Y. A human-aware robotic system for mobile robot navigating in multi-floor building with elevator. In Proceedings of the 2019 WRC Symposium on Advanced Robotics and Automation (WRC SARA), Beijing, China, 21–22 August 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 178–183.
12. Kim, J.; Jung, H. Robot Routing Problem of Last-Mile Delivery in Indoor Environments. *Appl. Sci.* **2022**, *12*, 9111. [CrossRef]
13. Servo-Robot. Laser Seam Tracking. 2023. Available online: https://servo-robot.com/laser-seam-tracking/ (accessed on 5 October 2023).
14. RoboDK. Offline Programming Software. 2023. Available online: https://robodk.com/simulation (accessed on 4 September 2023).
15. Robotmaster. Offline Programming Software for Robots. 2023. Available online: https://www.robotmaster.com/en (accessed on 11 March 2023).