

Article

Improved Design of LNG Marine Loading Arm Docking Method Based on TRIZ Theory

Jie Mei, Wuwei Feng ^{*}  and Zirong Liang

Faculty of Naval Architecture and Ocean Engineering, Zhejiang Ocean University, Zhoushan 316022, China

^{*} Correspondence: fengwuwei@163.com

Abstract: The LNG marine loading arm is a critical component for transferring LNG from vessels to onshore receiving stations. However, currently, the operation of LNG marine loading arms is still faced with issues such as a slow docking speed and significant environmental impacts from waves and wind. In this paper, we propose a set of feasible improvement schemes for the traditional LNG marine loading arm based on the theory of inventive problem solving (TRIZ). We utilized tools such as functional models, causal chain analysis, contradiction analysis, and Su-Field model analysis to develop these schemes. Our proposed improvements include using machine vision and automatic control to replace manual work, conducting finite element analysis and topology optimization of the LNG marine loading arm to improve its structure, and innovating the design of the end structure of the LNG discharge arm.

Keywords: LNG marine loading arm; TRIZ; finite element analysis; topological optimization; FLUID; machine design



Citation: Mei, J.; Feng, W.; Liang, Z. Improved Design of LNG Marine Loading Arm Docking Method Based on TRIZ Theory. *Appl. Sci.* **2023**, *13*, 4525. <https://doi.org/10.3390/app13074525>

Academic Editors: Pavol Božek, Tibor Krenicky and Yuri Nikitin

Received: 7 March 2023

Revised: 25 March 2023

Accepted: 31 March 2023

Published: 3 April 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Since the beginning of the twenty-first century, environmental problems caused by the excessive use of oil resources have come to the fore, and the global energy demand continues to grow, with an estimated annual growth of 1.2% [1]. In order to achieve a balance between energy and environmental issues, LNG (liquefied natural gas), as a clean energy source, is increasingly regarded as an ideal alternative to traditional fossil fuels and is used by many as a major energy source [2]. However, as natural gas resources are unevenly distributed across the planet, large energy consumers such as China need to import significant amounts of liquefied natural gas to meet their energy needs. Currently, the transportation of liquefied natural gas relies mainly on LNG ship transport to the wharf, where it is unloaded using the LNG marine loading arm, and with the help of unloading pumps, the LNG is sent to the storage tank of the LNG receiving station. Thus, the LNG marine loading arm is an important link between the LNG ship and the receiving station. In the past decade, many scholars have studied and analyzed problems related to the LNG marine loading arm and the connection between the LNG ship and the LNG marine loading arm.

Thaddeus C. Nwaoha [3] conducted a study on the complex operations and high-risk safety issues of LNG marine loading arm equipment and optimized its operation by utilizing a mixed algorithm. Xiaoling Liang et al. [4] conducted a theoretical study on the dynamic positioning of LNG ships under output constraints to maintain a relatively fixed position for the LNG marine loading arm, which has significant guiding value. Dongya Zhao et al. [5] performed experiments to investigate the influence of hull shaking on the LNG ship connection system. While these studies mainly focused on specific issues of the LNG unloading system or LNG marine loading arm and were mostly theoretical, it is challenging to apply their findings in a short period of time. Considering the current problems with the LNG docking system, few scholars have proposed complete and practical solutions. TRIZ has been an innovative method used by many researchers to solve

engineering and technical problems. Chino Uzoka et al. [6] applied TRIZ to CFD technology and designed a novel hybrid control valve. Nuri Sen et al. [7] used TRIZ to solve the tearing problem of the control arm in the processing and forming process without altering the required material and shape of the part. Sergio Tadeu Almeida et al. [8] used TRIZ to overcome the limitations of traditional six-axis robot machining and developed an EDM cutting robot end-effector.

This paper adopted TRIZ and the innovation principle of TRIZ. The research object was an LNG marine loading arm produced by a company in Shanghai, China. The aim was to address the issues of the slow docking speed and low accuracy resulting from environmental influences. This paper presents a set of feasible solutions designed to tackle these problems.

2. TRIZ Methods

TRIZ is a set of methods and theories for solving invention problems that Genrich Altshuller and his team developed by analyzing and summarizing 2.5 million high-quality patent documents [9]. TRIZ has been successfully applied in various fields, such as management innovation, design innovation, mechanical and electronic engineering, and software development. By applying TRIZ, breakthrough innovations can be achieved, and specific solutions for a system can be found.

Classical TRIZ includes theoretical analysis tools such as the Algorithm for Inventive Problem Solving, Su-Field model analysis, contradiction analysis, and analysis tools of the status quo of TRIZ. Additionally, functional models, functional analysis, and causal chain analysis have been added to the toolkit [10]. During problem solving, these analysis tools are utilized to break down the problem, establish an appropriate problem model, and then select the most suitable problem-solving tools to obtain a solution. To solve technical contradiction problems, 39 engineering parameters, the contradiction matrix, and 40 invention principles are applied [11]. To solve physical contradictions, the separation principle is utilized [12], and the matter field model and standard solution are used to implement minimal changes to the system to solve the problem. Furthermore, causal chain analysis is applied to determine the root cause of the problem. The application of S-curve analysis and the law of technological system evolution can be used to predict the next generation of products and achieve incremental or breakthrough innovations.

When applying TRIZ to solve an engineering problem, it is essential to define and describe the problem first. Then, the specific issue must be transformed into a general TRIZ problem, which involves establishing a TRIZ problem model [13]. This is followed by the selection of the appropriate TRIZ tool based on the problem model to obtain the corresponding solution model, which is the general solution to the general TRIZ problem. The final step involves obtaining specific engineering solutions through mapping, comparison, and other methods, along with the relevant verification and evaluation of the solutions. Figure 1 illustrates the solution process using TRIZ.

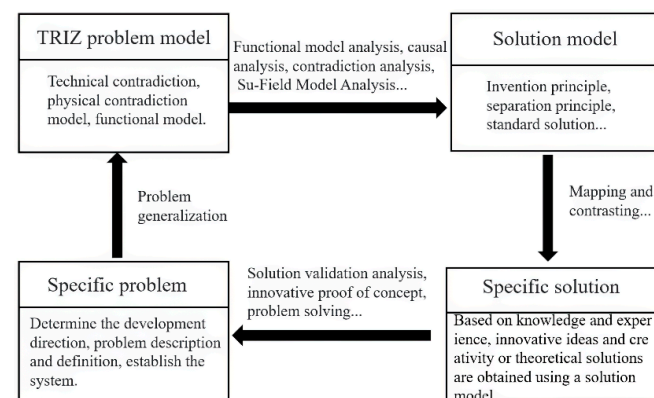


Figure 1. Flow chart of a TRIZ solution.

3. The Problem Analysis

3.1. Functional Models

The establishment of functional models for functional analysis can clarify the useful functions, functional levels, and performance levels (normal, excessive, insufficient), as well as the harmful functions of each component in the system [14]. Furthermore, functional models can assist researchers in gaining a more detailed understanding of the interactions between the system's components [15].

Currently, the process of docking the LNG marine loading arm is performed manually. Figure 2 depicts the working diagram of the LNG marine loading arm docking to the LNG ship. This docking process involves the LNG marine loading arm (along with the control system), the operator, and the LNG ship system. At least two or more operators are required to carry out the docking process. One operator is stationed on the LNG ship to guide the marine loading arm, while the other is stationed on land. The land-based operator needs to continuously control and adjust the LNG marine loading arm based on the feedback received from the shipboard operator and their observations so that the LNG marine loading arm can steadily approach the target and activate the terminal joint once the predetermined distance is reached. This completes the docking process. After analyzing and summarizing the functions of the above components, the functional grade and performance level of each component were determined. Consequently, a functional model of the current LNG marine loading arm docking scheme with the LNG ship was established, as shown in Figure 3.

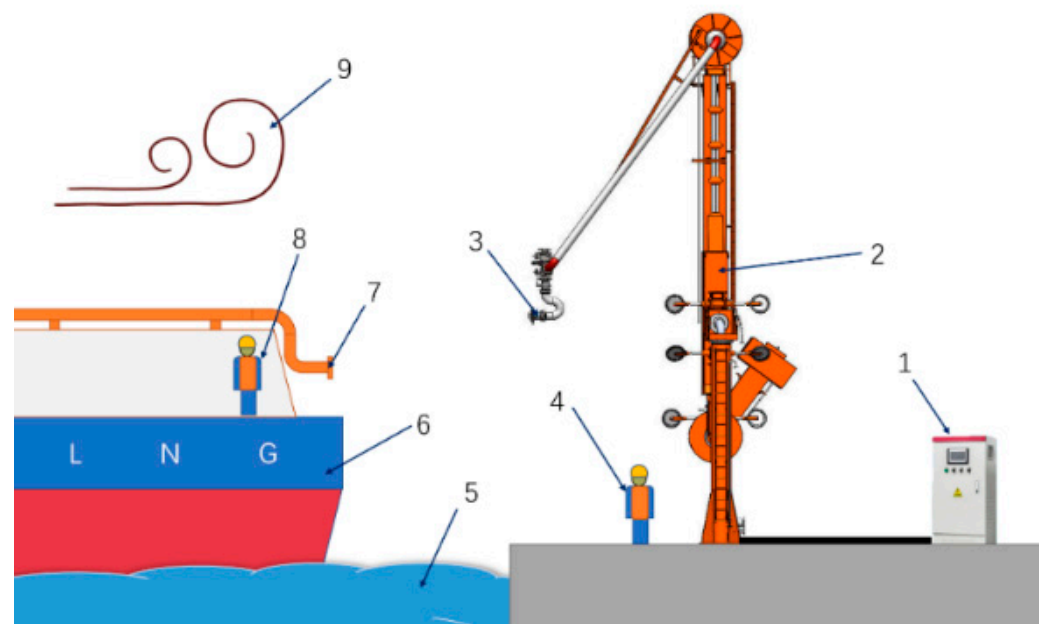


Figure 2. Working schematic diagram of LNG marine loading arm docking with LNG ship. 1—LNG marine loading arm control box; 2—LNG marine loading arm; 3—end joint of the LNG marine loading arm; 4—land operator; 5—wave; 6—LNG ship; 7—transportation pipe interface; 8—ship operator; 9—wind.

After analyzing the functional model, three main factors affecting the docking of LNG unloading were identified: (1) waves and wind can interfere with the docking process; (2) the land-based operator may not have sufficient information to guide the marine loading arm, relying only on observation and communication with the offshore operator; (3) the information received by the onshore operator may result in over- or under-operation of the LNG marine loading arm, which is not stable enough. To further study and find a solution to these problems, a causal analysis is needed.

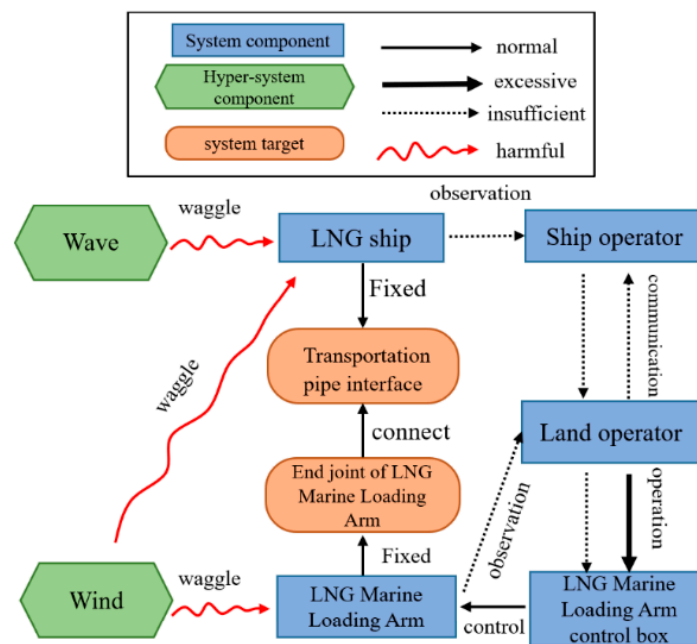


Figure 3. Functional model.

3.2. Causal Analysis

Causal analysis is an analytical method that establishes the relationship between the causes and results of events by constructing a causal chain [16]. The construction of a causal chain diagram enables in-depth analysis of technical system problems, identifying the root causes of problems and starting points for their solutions [10]. Figure 4 depicts the causal chain of problems caused by the LNG marine loading arm.

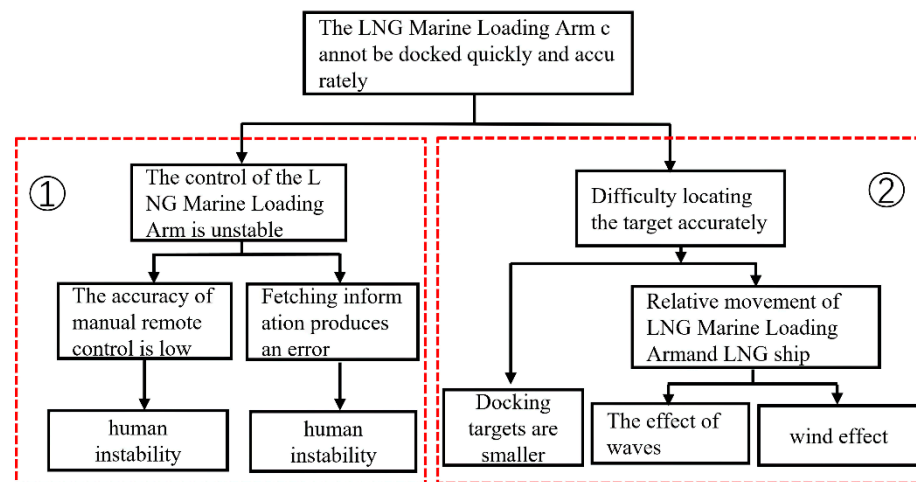


Figure 4. Causal chain analysis of problems.

Starting with the current issue of the LNG marine loading arm's inability to quickly and accurately dock, two fundamental problems can be identified, as depicted in the red dotted boxes in Figure 4: (1) the instability of the human operator results in the instability of the control of the LNG marine loading arm, ultimately leading to the failure of fast and accurate docking; (2) the position of the LNG marine loading arm and the LNG ship is subject to the influence of wind and waves, making it challenging to locate the docking target, thus resulting in the inaccurate and rapid docking of the LNG marine loading arm. Therefore, to address the problem of the LNG marine loading arm's inability to connect quickly and accurately, it is imperative to address these two fundamental problems first.

4. Innovative Design of Problem-Solving Method Based on TRIZ

4.1. Technical Contradiction Analysis and Invention Principle

TRIZ's 40 principles of invention serve as a guide for conflict resolution and innovative product design. Additionally, the 39 engineering parameters describe the problem space of the design problem, while the 40 invention principles describe the solution space of the design problem. Causality analysis can be used to convert the results into TRIZ problems, with parameters to be improved and worsened being converted into 39 general technical parameters. For instance, to address the difficulty of manual remote control, parameter No. 33, ease of manufacture, and parameter No. 28, measurement accuracy for information acquisition, are the two parameters to be improved. However, improving these parameters could lead to an increase in the time required for the task, which is referred to as the deterioration parameter, No. 25, loss of time. By utilizing the TRIZ contradiction matrix with the aforementioned parameters, the invention principle outlined in Table 1 can be obtained.

Table 1. Contradiction matrix table obtained by parameter.

Parameter	No. 25 Loss of Time
No. 33 ease of manufacture	4, 28, 10, 34
No. 28 measurement accuracy	32, 26, 28, 18

Table 1's invention principle was analyzed, and the appropriate principle was selected based on practical problems. In this case, parameter No. 28, mechanics substitution, can be utilized to address the issues of manual remote control difficulty and information acquisition errors. To address the difficulty of manual remote control, the control algorithm for the LNG marine loading arm can be programmed into a microcontroller. This would enable the replacement of manual operation with an electronic system. For information acquisition errors, a solution can be implemented through the use of cameras and sensors to collect data. Useful information can then be obtained by processing these data through a computer.

4.2. Innovative Design of Information Collection

In this approach, cameras are utilized in place of human eyes for acquiring the coordinate information of the target. There exist two challenges that must be addressed: firstly, identifying the docking target in the two-dimensional image captured by the camera; secondly, recognizing the target after obtaining its coordinates in the physical world. To tackle these two issues, this method employs a binocular camera to obtain depth information from the image. Subsequently, the image is processed by an algorithm to derive the required target coordinates. The process of obtaining target coordinate information is depicted in Figure 5.

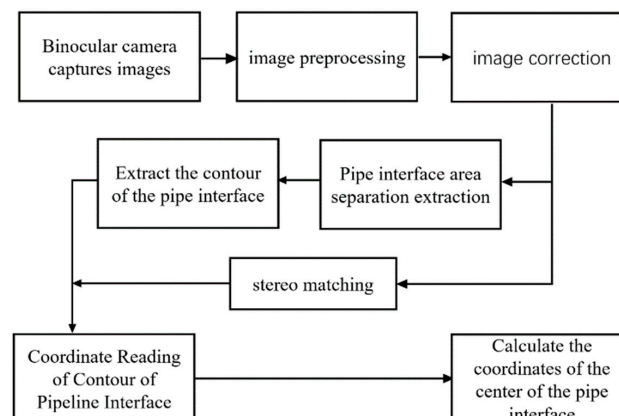


Figure 5. Flow chart of obtaining target coordinate information.

4.2.1. Target Image Recognition

During the operational process, distinguishing the uses of different pipelines can be achieved by assigning different colors to target interfaces. To separate the pipe mouth from the background, constructing color masks to cover irrelevant areas is a commonly used approach. To facilitate image processing, the RGB color space of the collected image is converted to the HSV color space [17]. The desired area can be approximately extracted by selecting the appropriate hue (H) value when performing image segmentation using the HSV color space. Based on the actual situation, the saturation (S) and value (V) can be set to further filter the interference points, resulting in the extraction of the required region. Figure 6 illustrates the final target extraction results.

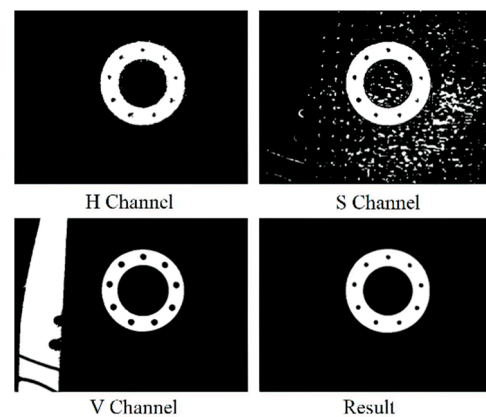


Figure 6. Results of target region extraction.

The findContours function in OpenCV was employed to identify the target contour [18–20]. Nevertheless, during practical implementation, a substantial amount of interference information was observed. As a result, all of the retrieved contours were sorted based on their size, and the largest contour was selected as the target contour. The final outcome is presented in Figure 7.

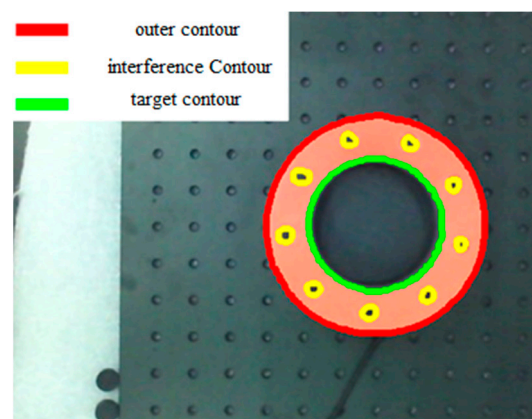


Figure 7. Final target contour diagram.

4.2.2. Obtaining the Coordinates of the Target

Using a binocular camera to capture two images of the same object simultaneously, the deviation of the target on the two images is calculated based on the principle of triangle approximation. This is used to obtain depth information, which is then used to calculate the three-dimensional coordinates in space. The principle of image depth calculation is shown in Figure 8. The binocular camera has two focal lengths, f , with O_L and O_R representing the optical centers of the left and right cameras, respectively. $O_L Z_L$ and $O_R Z_R$ represent the optical axes of the left and right cameras, respectively, with both axes being parallel

and separated by a distance of b . The point P represents the center of the target, with coordinates $P(X_c, Y_c, Z_c)$ in the coordinate system $X_L O_L Y_L Z_L$, with the left camera's optical center as the origin. $X_L O_L Y_L$ represents the imaging plane of the left camera, while $X_r O_r Y_r$ represents the imaging plane of the right camera. The imaging points of point P on the two imaging planes are $p_1(x_1, y_1)$ and $p_2(x_2, y_2)$.

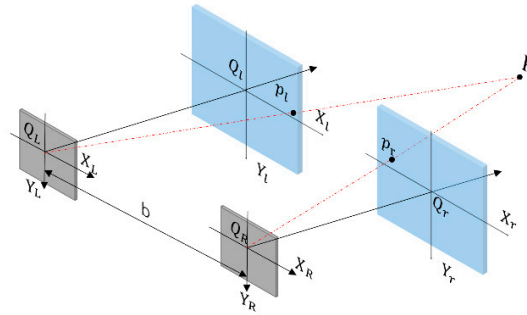


Figure 8. Schematic diagram of the image depth calculation.

Using the similar triangle principle, the coordinates of $p_1(x_1, y_1)$ and $p_2(x_2, y_2)$ can be related to $P(X_c, Y_c, Z_c)$ as follows:

$$\begin{cases} X_c = \frac{b \cdot x_1}{x_1 - x_2} \\ Y_c = \frac{b \cdot y_1}{x_1 - x_2} \\ Z_c = \frac{b \cdot f}{x_1 - x_2} \end{cases} \quad (1)$$

According to the formula, the three-dimensional coordinates of the target can be obtained by calculating the coordinates of points p_1 and p_2 on the imaging plane. As the target is a circular pipe opening, it is a symmetrical figure at its center, regardless of the angle chosen. Hence, the graphical moment method was employed to calculate the target center coordinates [21–23]. The final result is presented in Figure 9. The pixel coordinate (x, y) is represented by $f(x, y)$, which corresponds to the gray value. The zero-order moment and first-order moment of the graph can be, respectively, expressed as

$$m_{00} = \iint f(x, y) dx dy \quad (2)$$

$$\begin{cases} m_{10} = \sum_x \sum_y x f(x, y) \\ m_{01} = \sum_x \sum_y y f(x, y) \end{cases} \quad (3)$$

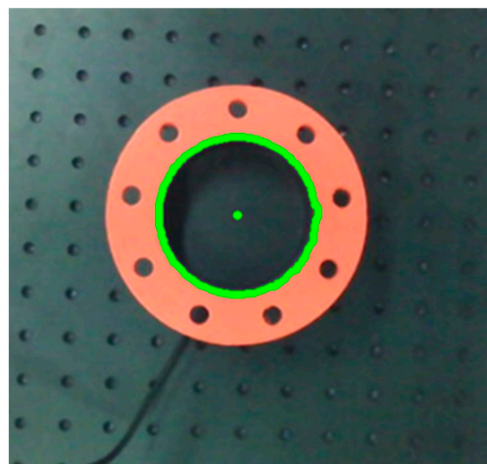


Figure 9. The center of the target image.

The coordinates of the target center in the image can be expressed as follows:

$$\begin{cases} x_p = \frac{m_{10}}{m_{00}} \\ y_p = \frac{m_{01}}{m_{00}} \end{cases} \quad (4)$$

By utilizing Equation (5), the coordinates of the object in the image are transformed into the coordinates of the camera imaging plane. The value of $(x_1 - x_2)$ is then calculated and substituted into Equation (1), which enables the determination of the three-dimensional coordinates of the target center.

$$\begin{bmatrix} x_p \\ y_p \\ 1 \end{bmatrix} = \frac{1}{Z_c} \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} \quad (5)$$

4.2.3. Experimental Verification

The experiment involved comparing the distance measured in reality with the distance calculated using the binocular camera depth values, in order to verify the feasibility of the proposed approach. The parameters of the binocular camera used are shown in Table 2. The camera was connected to a computer via a data cable, and the experimental program was written in C++ and run in a VS2017 environment with the OpenCV library configured.

Table 2. Parameters of the camera.

Main Parameters	Parameter Values
Sensor Size	1/3"
Individual Pixel Size	3.75 μm $\times$ 3.75 μm
Baseline	6 cm
Standard Lens	3.4 mm focal length, distortion < 0.3%
Camera Resolution and Frequency	2560 $\times$ 720@30 fps 1280 $\times$ 480@30 fps

During the experiment, the binocular camera was fixed on a triangular support and used to capture images of the target from different distances, as shown in Figure 10. The captured images were processed in the program to obtain depth values, which were then compared with the actual measured distances. The final experimental results are shown in Table 3. Compared with the actual measured values, the maximum error in the distance calculated using the binocular camera approach was in the millimeter range, and the relative error did not exceed 1%. This level of error is acceptable for large equipment such as LNG marine loading arms. Therefore, this method is feasible.

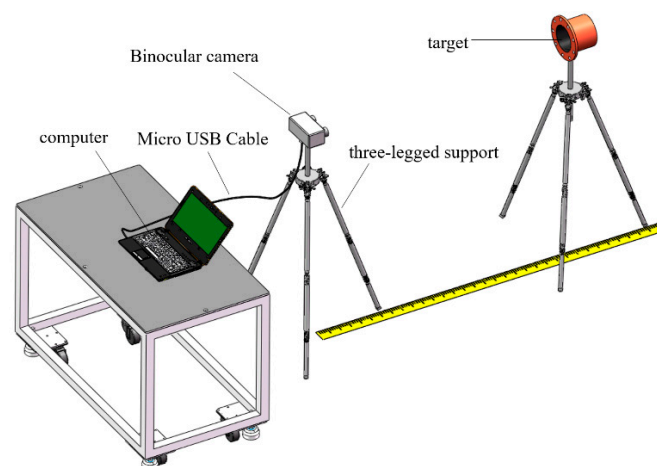


Figure 10. Schematic diagram of the experiment.

Table 3. Comparison of the results.

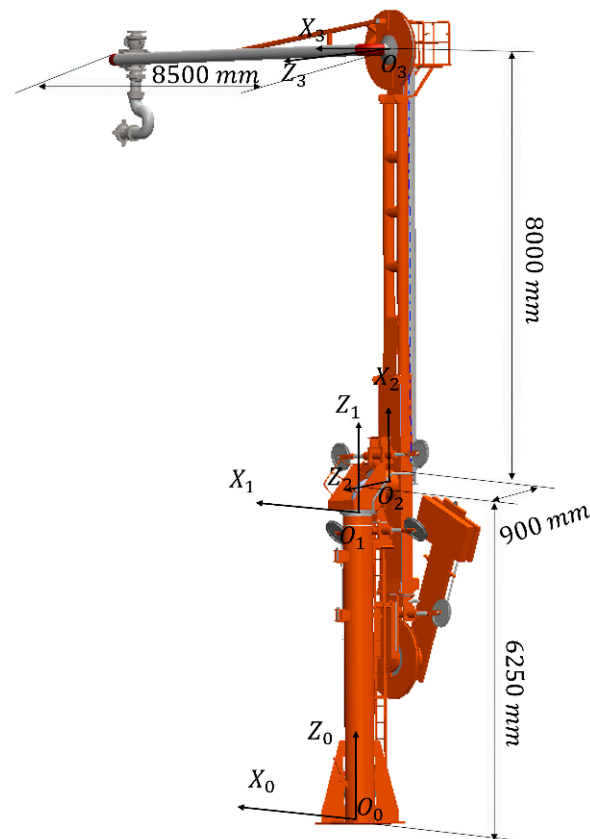
Serial Number	Distance Measurement	Distance Calculation	Absolute Error	Relative Error
	(mm)	(mm)	(mm)	
1	497	497.2	0.2	0.03%
2	601	598.5	2.5	0.41%
3	698	696.9	1.1	0.16%
4	797	794.7	2.3	0.29%
5	900	894.4	5.6	0.63%
6	1000	990.1	9.9	0.99%
7	1103	1097.0	6.0	0.54%
8	1202	1193.6	8.4	0.69%

4.3. Design of Automatic Control of LNG Marine Loading Arm

As depicted in Figure 11, the LNG marine loading arm appears to be a three-axis mechanical arm. To establish the relationship between adjacent rods through the coordinate system and express it in the form of a matrix, the $D-H$ method was employed. This method facilitates the establishment of the kinematics equation of the marine loading arm [24]. The homogeneous matrix of each adjacent member can be represented as follows:

$${}^{i-1}_iT = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & \alpha_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -d_i s\alpha_{i-1} \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & d_i c\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

where $c\theta_n = \cos\theta_n$, and $s\theta_n = \sin\theta_n$.

**Figure 11.** Coordinate system diagram of LNG marine loading arm link.

The parameters listed in Table 4 are substituted into Equation (6) in order to derive the transformation matrix for each link.

$${}^0_1T = \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0 \\ s\theta_1 & c\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

$${}^1_2T = \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s\theta_2 & c\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

$${}^2_3T = \begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & a_2 \\ s\theta_3 & c\theta_3 & 0 & d_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9)$$

Table 4. D–H parameter table.

Link (<i>i</i>)	$\alpha_{i-1}/(^{\circ})$	a_{i-1}	d_i	$\theta_i/(^{\circ})$
1	0	0	0	θ_1
2	90	0	0	θ_2
3	0	a_2	d_3	θ_3

Multiplying the transformation matrices of each link, the expression for the position of the end of the LNG marine loading arm relative to the base can be obtained.

$${}^0_3T = {}^0_1T(\theta_1){}^1_2T(\theta_2){}^2_3T(\theta_3) \quad (10)$$

According to the expression, it is possible to obtain all possible solutions for the variables θ_1 , θ_2 , and θ_3 , followed by screening out the solutions that meet the specified requirements. This process is known as finding the inverse solution for the manipulator. To control the LNG marine loading arm, the solution program that satisfies the requirements can be programmed into the microcontroller [25]. In order to verify the feasibility of the proposed solution, a model of the LNG marine loading arm was printed using 3D printing technology and a motor was installed. The inverse solution was calculated and written in C language and then burned onto a microcontroller. Ultimately, the LNG marine loading arm can be controlled freely to move to a specified coordinate position. As shown in Figure 12, only by inputting the coordinates of the target into the microcontroller can the LNG marine loading arm model accurately move in front of the target.

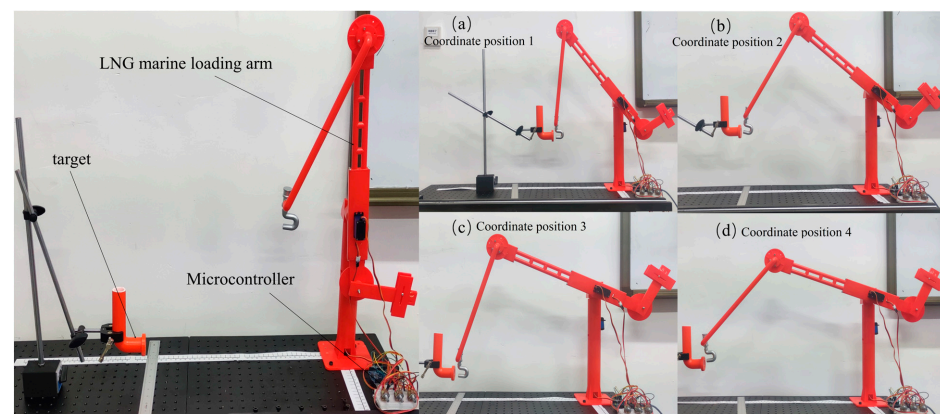


Figure 12. LNG marine loading arm model.

4.4. Su-Field Model and Standard Solutions

Su-Field model analysis is a crucial analytical tool in TRIZ. This approach involves analyzing the technical system's components and their interrelations to develop a Su-Field model. Through the use of symbolic language, this model helps to accurately and precisely describe the various contradictory problems that arise within the system [26].

During the automatic docking process, the effect between the LNG marine loading arm and the LNG ship pipeline is not sufficient due to the influence of wind and waves, which leads to the inability to dock quickly and accurately. A Su-Field model for the problem was established, as shown in Figure 13. For a complete model with insufficient effect, there are three general solutions based on the Su-Field model: (1) replace the original initial field (or the initial field and substance) with another field (or another field and substance); (2) add another field to strengthen the useful effect; (3) insert the substance and add another field to improve the useful effect.

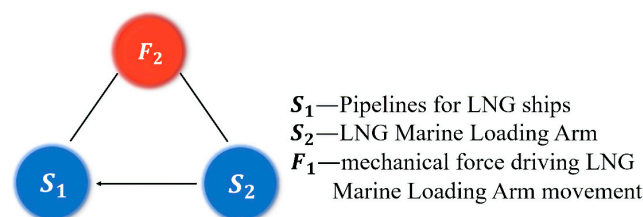


Figure 13. The Su-field model of the problem.

Based on the causal chain associated with problem two, two improvement plans are proposed using solutions (1) and (3).

Plan 1: According to solution (1) and the causal chain analysis, the structure of the LNG marine loading arm is redesigned to reduce the windward area affected by the wind. This will reduce the impact of wind on the LNG marine loading arm and improve the difficulty of accurately positioning the target. The improved Su-Field model is shown in Figure 14a.

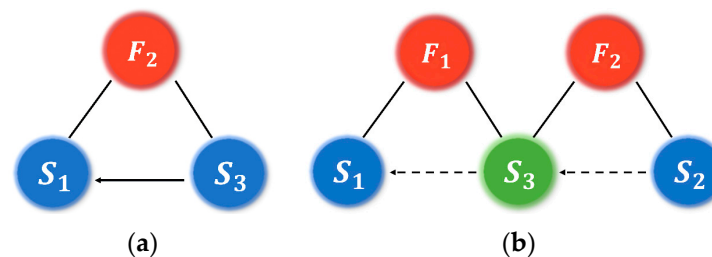


Figure 14. The improved Su-Field model. (a) Plan 1; (b) Plan 2.

Plan 2: According to solution (3) and the causal chain analysis, a device named S_3 is designed to address the small target issue. The device S_3 is installed at the end of the marine loading arm. Through the mechanical force F_2 generated by this device, it assists the LNG marine loading arm and the LNG ship pipeline in completing the docking quickly and accurately. The improved Su-Field model is shown in Figure 14b.

4.5. Technical Contradiction Analysis and Invention Principle

To implement Plan 1, it is necessary to transform the parameters that require improvement and those that may deteriorate into 39 general technical parameters. When it comes to reducing the windward area of the LNG marine loading arm in order to minimize the wind force it experiences, the parameter that requires improvement is identified as No.11, which refers to stress or pressure. However, such a reduction in the windward area could negatively impact the structural strength of the arm and compromise its operational stability. Hence, the parameter that may deteriorate is No.13, stability of the object's composition.

By utilizing these parameters to search for the TRIZ contradiction matrix, we can derive the inventive principles outlined in Table 5.

Table 5. Contradiction matrix table of Plan 1.

Parameter	No. 13 Stability of Object's Composition
No. 11 stress of pressure	35, 33, 2, 40

For Plan 2, the objective is to improve the alignment with smaller targets, so the parameter to be improved is the area of the moving object, which is No. 5. According to Plan 2, adding a device will increase the required power, so the deteriorating parameter is No. 21, power. Referring to the TRIZ contradiction matrix, the inventive principles are shown in Table 6.

Table 6. Contradiction matrix table of Plan 2.

Parameter	No. 21 Power
No. 5 area of moving object	19, 10, 32, 18

4.6. The Method of Numerical Analysis Is Adopted for Innovative Design

Applying Invention Principle No. 2, taking out, which involves removing useful or harmful parts or attributes from the whole, can be beneficial. In the case of Plan 1, this principle is applied to the LNG marine loading arm by removing parts that have little influence on the structural strength. This results in a reduction in the windward area while having minimal impact on the arm's strength. Thus, topology optimization can be utilized to improve the structure of the LNG marine loading arm [27]. Firstly, the optimization position is determined through fluid simulation, followed by the optimization process.

4.6.1. Determination of the Location of Optimization

The finite element model was imported into Fluent and defined, and the SST K-omega turbulence model [28] was selected. It is worth noting that ground objects can significantly impact the movement of air flow, leading to a reduction in wind speed due to air flow friction. The effect of ground roughness on wind speed diminishes with increasing height as the frictional force becomes weaker. Consequently, the average wind speed changes exponentially with the ground's roughness and height, following the expression:

$$\frac{\overline{v}_1(z)}{\overline{v}_b} = \left(\frac{z}{z_b} \right)^\alpha \quad (11)$$

where z represents the height of arbitrary wind, z_b represents the standard value of the reference height, $\overline{v}_1(z)$ and $\overline{v}_b$ represent the wind speed at heights z and z_b , respectively, and α represents the coefficient of ground roughness, which was set to 0.12 according to the working environment in this paper [29,30].

Following the Chinese national standard, we set the reference height z_b to 10 m and $\overline{v}_b$ to 50 m/s for the calculations. We developed a UDF velocity inlet that conforms to the exponential distribution for the model's velocity inlet. The operating pressure was set to standard atmospheric pressure, with a temperature of 20 °C, and dynamic viscosity of $\mu = 1.42 \times 10^{-5} \text{ m}^2/\text{s}$, and a density of $\rho = 1.20 \text{ kg}/\text{m}^3$. The model selected the velocity inlet and pressure outlet. The SIMPLE solver was used to solve the model.

Figure 15 depicts the velocity cross-section of the external flow field in the discharge arm after being solved. The figure demonstrates that the air flow experiences an obstruction in the marine loading arm, resulting in a disturbance and reduction in air flow speed, consequently creating a vortex at the rear. As a result, the air flow velocity through the LNG marine loading arm weakens to varying degrees.

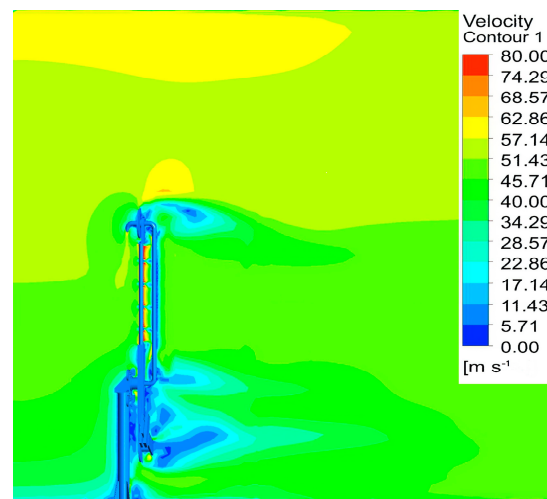


Figure 15. Velocity cross-section of the LNG marine loading arm flow field.

Figure 16 depicts the velocity distribution of the transverse section of the LNG feeder arm at 2 m distance intervals. The results demonstrate that the obstruction caused by the marine loading arm leads to a significant reduction in the flow velocity at $Y = 2$ m, $Y = 4$ m, $Y = 6$ m, and $Y = 14$ m. The corresponding areas of the marine loading arm include the column, the counterweight block and its support, and the upper and lower rope wheels.

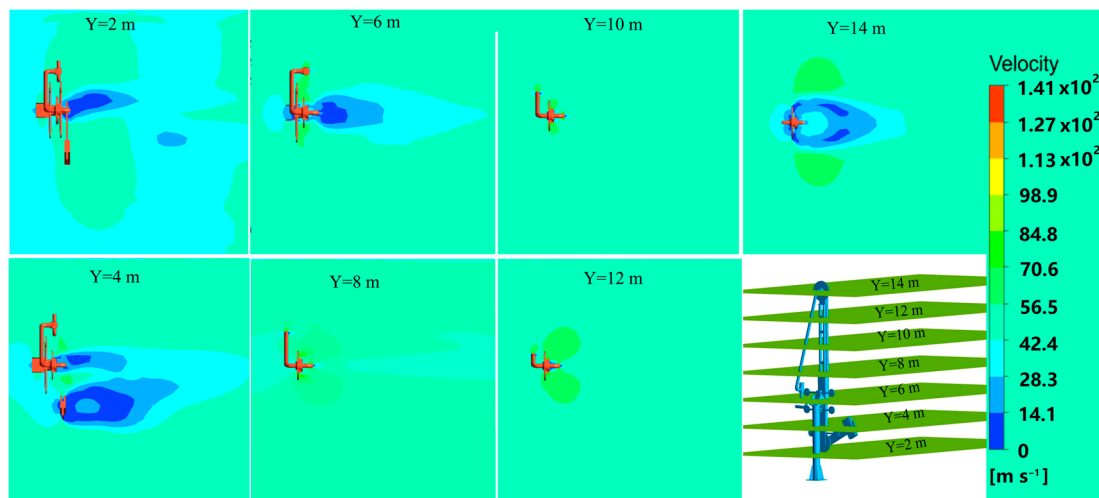


Figure 16. Velocity distribution in different sections of the LNG marine loading arm flow field.

4.6.2. Topological Optimization

After conducting an analysis of the external flow field simulation results of the marine loading arm, it was determined that several components, including the upper rope wheel, column, lower rope wheel, counterweight, and counterweight support, are subjected to considerable loads. As the column houses a complex pipeline system, any alterations to its structure could result in repercussions for the unloading transmission system. Therefore, the optimization analysis was restricted to the upper and lower rope wheels, along with the counterweight support.

Based on the established finite element model of the rope wheel and counterweight support shown in Figure 17, the topology optimization of their structure was carried out by defining the optimization and non-optimization areas according to the simulation results. The objective of the optimization, as indicated by [31], was to minimize the compliance, which corresponds to maximizing stiffness. Additionally, the target volume was set as a constraint to minimize the structural deformation energy under a given

load. The volume retention rates for the rope wheel and counterweight support topology optimization settings were set to 35% and 30%, respectively. The optimization process used an iterative approach, with an iteration accuracy of 5×10^{-4} and 59 and 37 iterations for the rope wheel and counterweight support, respectively. The optimization criterion method was employed for the topology optimization process.

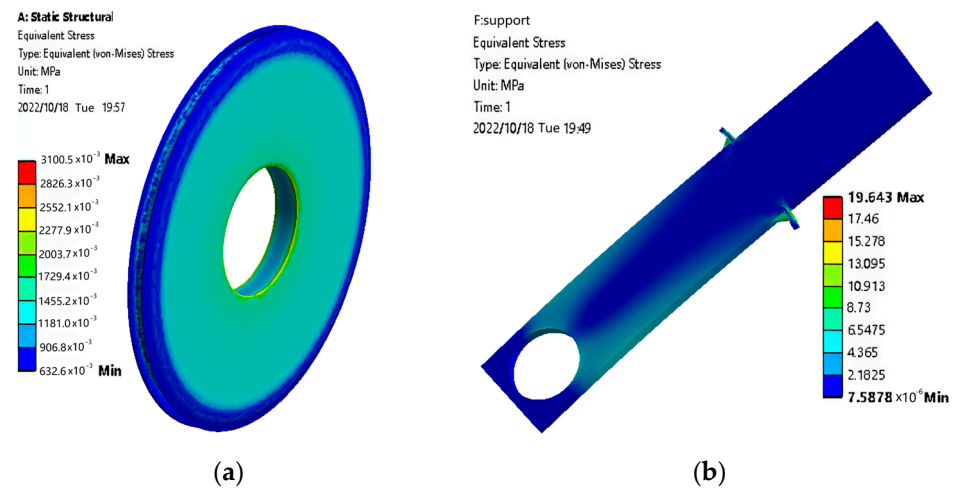


Figure 17. Stress cloud diagram of topological targets. (a) Rope wheels; (b) counterweight support.

Based on the topological results presented in Figures 18 and 19, and in conjunction with the manufacturing process, the new structure can be achieved through selective material reduction or additive processing.

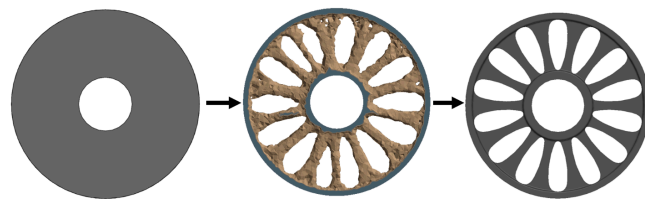


Figure 18. Rope wheel optimization process.

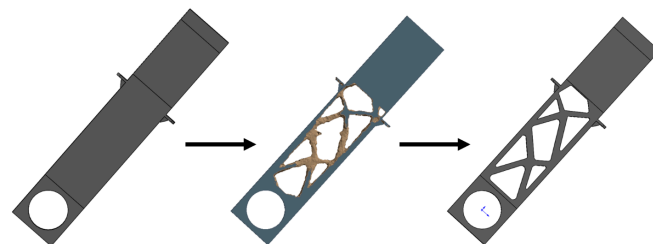


Figure 19. Optimization process of counterweight support.

4.6.3. The Results after Optimization

Finite element analysis was carried out to assess the improved structure, and Tables 7 and 8 show the relevant parameter changes before and after the improvement. The improved rope wheel structure exhibits a 59.34% reduction in mass and a 41.9% reduction in maximum wind face surface area compared to the initial structure. This reduction in the wind face area is advantageous in mitigating the influence of wind on the marine loading arm. However, the maximum stress and deformation of the rope wheel are increased after the improvement. Nonetheless, the yield limit of the improved structure, which is 355 Mpa, satisfies the requirements for strength and stiffness. In terms of the counterweight support, the total mass of the improved mechanism is 29.38% compared to the initial structure

mass, with a 52.95% reduction in the mass of the optimized region. The maximum stress and maximum total deformation are only slightly increased, meeting the requirements for strength and stiffness. The surface area of the optimized region is reduced by 52.7%, which effectively reduces the impact of wind.

Table 7. Comparison of relevant parameters of upper and lower rope wheels before and after improvement.

Upper and Lower Rope Wheels	Initial Structure	Improved Structure
Mass (kg)	700.97	285.01
Maximum windward surface area (m ²)	1.24	0.72
Maximum stress (MPa)	3.10	12.47
Maximum total deformation (mm)	0.008	0.017

Table 8. Comparison of relevant parameters of counterweight support before and after improvement.

Counterweight Support	Initial Structure	Improved Structure
Mass (kg)	693.70	326.34
Surface area (m ²)	1.10	0.52
Maximum stress (MPa)	19.64	21.149
Maximum total deformation (mm)	0.25	0.43

Due to variations in the pressure exerted on the marine loading arm at different positions, the LNG marine loading arm was divided into n regions for separate calculations. The more regions the arm is divided into, the more accurate the calculations will be. However, for the sake of convenience, the LNG marine loading arm was divided into 20 regions, as shown in Figure 20. The wind force acting on the marine loading arm can be expressed as follows:

$$F_i = S_i(P_i - P'_i) \quad (12)$$

$$F_{all} = \sum_{i=1}^n S_i(P_i - P'_i) \quad (13)$$

where F_i represents the wind force of the LNG marine loading arm at the detection position, S_i is the ratio of the area to the detection area, P_i is the pressure in the high-pressure area of the LNG marine loading arm, P'_i is the pressure in the back-pressure area of the LNG marine loading arm, and F_{all} represents the total wind force of the LNG marine loading arm.

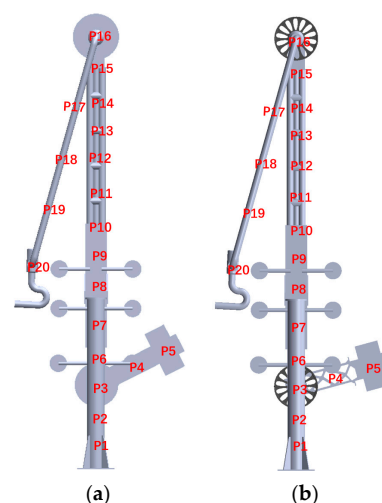


Figure 20. Detection and analysis of the position distribution of the LNG marine loading arm. (a) Structure before improvement; (b) structure after improvement.

According to the data in Table 9, it can be calculated that the total wind force acting on the LNG marine loading arm assembly before optimization is 27.7 KN. After optimization, the total wind force is reduced to 19.9 KN, representing a wind force reduction of 28.1%.

Table 9. The data before and after optimization for the LNG unloading arm.

Position	Before Optimization					After Optimization					
	Area (m²)	High Pressure (Pa)	Negative Pressure (Pa)	Pressure Difference (Pa)	Wind Load (N)	Area (m²)	High Pressure (Pa)	Negative Pressure (Pa)	Pressure Difference (Pa)	Wind Load (N)	
1	0.62	887.86	−326.69	1214.55	753.02	0.62	887.86	−326.69	1214.55	753.02	
2	0.57	1093.27	−1095.80	2189.07	1247.77	0.57	1093.27	−1095.80	2189.07	1247.77	
3	1.54	1220.78	−1590.12	2810.90	4328.79	1.02	1210.14	837.93	372.21	379.65	
4	0.91	679.57	−846.43	1526.00	1388.66	0.33	285.70	−1462.22	1747.92	576.81	
5	1.18	1185.74	−772.82	1958.56	2311.10	1.18	1185.74	−772.82	1958.56	2311.10	
6	0.5	1324.82	−1067.53	2392.34	1196.17	0.5	1324.82	−1067.53	2392.34	1196.17	
7	0.61	1404.55	−1169.78	2574.33	1570.34	0.61	1404.55	−1169.78	2574.33	1570.34	
8	0.6	1164.99	−818.47	1983.46	1190.08	0.6	1164.99	−818.47	1983.46	1190.08	
9	0.59	1493.05	−1060.75	2553.79	1506.74	0.59	1493.05	−1060.75	2553.79	1506.74	
10	0.6	52.02	−724.62	776.64	465.98	0.6	52.02	−724.62	776.64	465.98	
11	0.6	283.24	−113.58	396.81	238.09	0.6	283.24	−113.58	396.81	238.09	
12	0.6	362.04	−366.57	728.61	437.16	0.6	362.04	−366.57	728.61	437.16	
13	0.6	460.62	−333.54	794.16	476.50	0.6	460.62	−333.54	794.16	476.50	
14	0.6	410.81	−92.54	503.35	302.01	0.6	410.81	−92.54	503.35	302.01	
15	0.86	1621.35	−1319.59	2940.93	2529.20	0.86	1621.35	−1319.59	2940.93	2529.20	
16	1.73	1389.85	−1566.51	2956.36	5114.50	1.21	624.37	−1108.11	1732.48	2096.31	
17	0.38	1089.16	−701.12	1790.27	680.30	0.38	1089.16	−701.12	1790.27	680.30	
18	0.39	1585.12	−204.26	1789.38	697.86	0.39	1585.12	−204.26	1789.38	697.86	
19	0.39	1518.31	−266.86	1785.16	696.21	0.39	1518.31	−266.86	1785.16	696.21	
20	0.79	542.96	−272.35	815.30	644.09	0.79	542.96	−272.35	815.30	644.09	
Total wind load					27,774.57						19,995.40

4.7. Innovative Design Using Mechanical Design Methods

Based on the invention principle obtained from the contradiction matrix of Plan 2, combined with the actual situation, Invention Principle No. 10, the preliminary action principle, was used as a guide, and it manifests in two aspects: (1) pre-applying necessary changes to the object (wholly or partially); (2) pre-positioning the object at the optimal location to enable it to act at the earliest opportunity. Using a relatively large area, the target is pre-acted in the area, and then docking is performed. An auxiliary docking device designed according to this principle is shown in Figure 21, where the frame area is a relatively large docking area. After the target enters this area, the device will fix and clamp the target in the center under the drive of the hydraulic cylinder. Moreover, this device can solve the problem of the slight movement of the target caused by wind and waves, greatly improving the accuracy of docking.

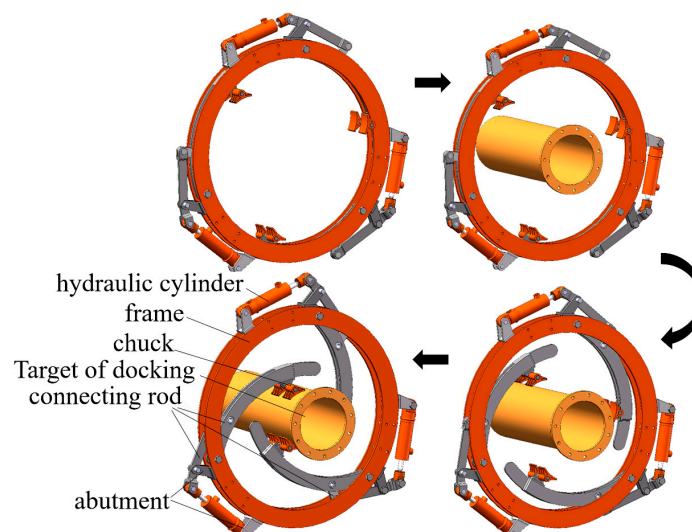


Figure 21. Working principle of the auxiliary docking device.

As shown in Figure 22, the auxiliary docking device is installed on the LNG marine loading arm joint. The entire device consists of the auxiliary docking device, the LNG marine loading arm docking joint, the fixing device, the Cr-coated shaft, the spring, and the linear bearing. Due to the use of the Cr-coated shaft and linear bearing structure, when the auxiliary docking device fixes the target, the remaining five degrees of freedom are constrained, leaving only one degree of freedom for linear motion in the direction of the target. This guides the LNG marine loading arm docking joint to move towards the target direction and complete the docking.

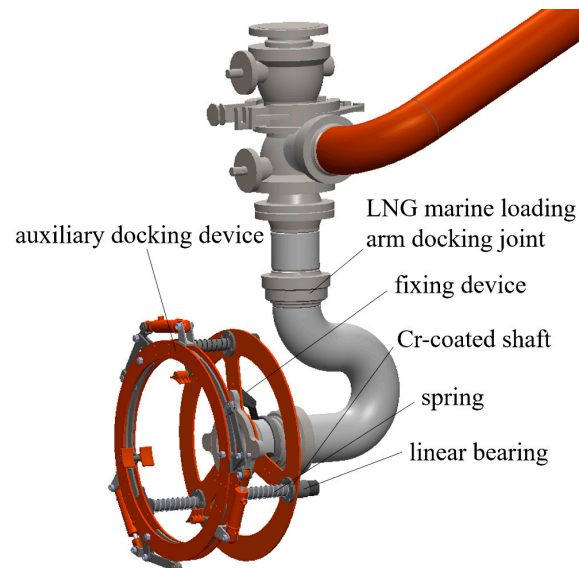


Figure 22. Joint after installing the auxiliary docking device.

5. Conclusions

This study used TRIZ to investigate the slow docking speed and low accuracy of LNG marine loading arms and presented a set of improvement schemes. Functional models, causal chain analysis, Su-Field model analysis, and other tools were used to make improvements to traditional LNG marine loading arms, and a method to improve the control mode, structure optimization, and mechanism design was proposed. The main conclusions are as follows.

Based on the functional model and causal chain analysis, this paper identified problems in the docking process of LNG marine loading arms and found corresponding solutions using the contradiction analysis method.

Using the Su-Field model, standard solution, and invention principle, three improvement methods were generated and verified: (1) replacing manual operation with machine vision and automatic control; (2) conducting finite element analysis and topology optimization on the marine loading arm to reduce the wind influence and weight; (3) innovative design of the terminal structure of the marine loading arm to increase the docking accuracy.

This paper's research presents practical and innovative applications of TRIZ in improving the docking method of LNG marine loading arms. In contrast to previous studies, this paper presents a complete set of feasible solutions, and their effects were verified. The proposed scheme can address existing issues with LNG marine loading arms, enabling automatic docking, which is highly feasible and aligned with future development trends.

6. Patents

The auxiliary docking device presented in this work has a utility model patent granted by the China National Intellectual Property Administration, patent number ZL 2021 2 2831894.7.

Author Contributions: Conceptualization, J.M. and W.F.; methodology, J.M.; software, Z.L.; validation, W.F.; resources, W.F.; data curation, J.M.; writing—original draft preparation, J.M. and W.F.; writing—review and editing, W.F.; visualization, W.F., J.M. and Z.L.; supervision, J.M.; project administration, W.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Dinghai District School-site Cooperation Project (2019C3105) and Oil Transfer Arm Automatic Docking Technology Research and Development Project between Shanghai Eminent Enterprise Development Co., Ltd. and Zhejiang Ocean University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data used to support the findings of this study are included within the article.

Acknowledgments: Thanks to engineer Xu Jie from Shanghai Eminent Enterprise Development Co., Ltd. for the technical and resource support.

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

References

1. The Outlook for Energy: A View to 2030. Available online: www.exxonmobil.com (accessed on 25 November 2022).
2. Kumar, S.; Kwon, H.-T.; Choi, K.-H.; Lim, W.; Cho, J.H.; Tak, K.; Moon, I. LNG: An Eco-Friendly Cryogenic Fuel for Sustainable Development. *Appl. Energy* **2011**, *88*, 4264–4273. [\[CrossRef\]](#)
3. Nwaoha, T.C. Inclusion of Hybrid Algorithm in Optimal Operations of Liquefied Natural Gas Transfer Arm under Uncertainty. *Ships Offshore Struct.* **2014**, *9*, 514–524. [\[CrossRef\]](#)
4. Liang, X.; Zhang, Y.; Ge, S.S.; How, B.V.E.; Li, D. Dynamic Control for LNG Carrier with Output Constraints. *IET Contr. Theory Appl.* **2022**, *16*, 729–740. [\[CrossRef\]](#)
5. Zhao, D.; Hu, Z.; Chen, G. Experimental Investigation on Dynamic Responses of FLNG Connection System during Side-by-Side Offloading Operation. *Ocean Eng.* **2017**, *136*, 283–293. [\[CrossRef\]](#)
6. Uzoka, C.; Mishra, R. Integration of TRIZ and CFD to New Product Development Process. *Int. J. Comput. Fluid Dyn.* **2020**, *34*, 418–437. [\[CrossRef\]](#)
7. Sen, N.; Baykal, Y.; Civek, T. Prevention of Tearing Failure during Forming of Lower Control Arm via TRIZ Methodology. *J. Mater. Eng. Perform.* **2021**, *30*, 7721–7729. [\[CrossRef\]](#)
8. Almeida, S.T.; Mo, J.; Bil, C.; Ding, S.; Wang, X. Conceptual Design of a High-Speed Wire EDM Robotic End-Effector Based on a Systematic Review Followed by TRIZ. *Machines* **2021**, *9*, 132. [\[CrossRef\]](#)
9. Chai, K.-H.; Zhang, J.; Tan, K.-C. A TRIZ-Based Method for New Service Design. *J. Serv. Res.* **2005**, *8*, 48–66. [\[CrossRef\]](#)
10. Liu, W.; Cao, G.; Tan, R. Research on Optimization of TRIZ Application Driven by Design Needs and Targets. *Procedia CIRP* **2016**, *39*, 33–38. [\[CrossRef\]](#)
11. Petković, D.; Issa, M.; Pavlović, N.D.; Zentner, L. Application of the TRIZ Creativity Enhancement Approach to Design of Passively Compliant Robotic Joint. *Int. J. Adv. Manuf. Technol.* **2013**, *67*, 865–875. [\[CrossRef\]](#)
12. Savransk, S.D. *Engineering of Creativity*; CRC Press: New York, NY, USA, 2002.
13. Wang, Y.-H.; Lee, C.-H.; Trappey, A.J.C. Service Design Blueprint Approach Incorporating TRIZ and Service QFD for a Meal Ordering System: A Case Study. *Comput. Ind. Eng.* **2017**, *107*, 388–400. [\[CrossRef\]](#)
14. Cao, G.Z.; Guo, H.X.; Liang, T.; Tan, R.H. Function Modeling, Solving and Simulation Based on Effect in TRIZ. *AMR* **2011**, *418–420*, 2190–2194.
15. Efimov-Soini, N.K.; Chechurin, L.S. Method of Ranking in the Function Model. *Procedia CIRP* **2016**, *39*, 22–26. [\[CrossRef\]](#)
16. Aurisicchio, M.; Bracewell, R.; Armstrong, G. The Function Analysis Diagram: Intended Benefits and Coexistence with Other Functional Models. *AIEDAM* **2013**, *27*, 249–257. [\[CrossRef\]](#)
17. Alqudah, A.M.; Alqudah, A. Improving Machine Learning Recognition of Colorectal Cancer Using 3D GLCM Applied to Different Color Spaces. *Multimed. Tools Appl.* **2022**, *81*, 10839–10860. [\[CrossRef\]](#)
18. Nandal, A.; Bhaskar, V.; Dhaka, A. Contrast-based Image Enhancement Algorithm Using Grey-scale and Colour Space. *IET Signal Process.* **2018**, *12*, 514–521. [\[CrossRef\]](#)
19. Laganieri, R. *OpenCV 2 Computer Vision Application Programming Cookbook: Over 50 Recipes to Master This Library of Programming Functions for Real-Time Computer Vision*; Packt Publishing: Birmingham, UK, 2011.
20. Kubrikov, M.V.; Saramud, M.V.; Karaseva, M.V. Method for the Optimal Positioning of the Cutter at the Honeycomb Block Cutting Applying Computer Vision. *IEEE Access* **2021**, *9*, 15548–15560. [\[CrossRef\]](#)
21. Itoh, M.; Chua, L.O. Imitation of visual illusions via openCV and CNN. *Int. J. Bifurc. Chaos* **2008**, *18*, 3551–3609. [\[CrossRef\]](#)
22. Žunić, J.; Hirota, K.; Rosin, P.L. A Hu Moment Invariant as a Shape Circularity Measure. *Pattern Recognit.* **2010**, *43*, 47–57. [\[CrossRef\]](#)
23. Žunić, D.; Žunić, J. Shape Ellipticity from Hu Moment Invariants. *Appl. Math. Comput.* **2014**, *226*, 406–414. [\[CrossRef\]](#)

24. Li, Y.; Wang, L.; Chen, B.; Wang, Z.; Sun, P.; Zheng, H.; Xu, T.; Qin, S. Optimization of Dynamic Load Distribution of a Serial-Parallel Hybrid Humanoid Arm. *Mech. Mach. Theory* **2020**, *149*, 103792. [[CrossRef](#)]
25. Pertuz, S.A.; Llanos, C.; Pena, C.; Munoz, D. A Parallel System-on-Chip Approach for Impedance Controller for a 7-DoF Robotic Hand. *Analog Integr. Circuits Process.* **2021**, *106*, 195–204. [[CrossRef](#)]
26. Song, M.J.; Lee, J.-G.; Park, J.-M.; Lee, S. Triggering Navigators for Innovative System Design: The Case of Lab-on-a-Chip Technology. *Expert Syst. Appl.* **2012**, *39*, 12451–12459. [[CrossRef](#)]
27. Yao, P.; Zhou, K.; Lin, Y.; Tang, Y. Light-Weight Topological Optimization for Upper Arm of an Industrial Welding Robot. *Metals* **2019**, *9*, 1020. [[CrossRef](#)]
28. Yu, H.; The, J. Validation and Optimization of SST K-Omega Turbulence Model for Pollutant Dispersion within a Building Array. *Atmos. Environ.* **2016**, *145*, 225–238. [[CrossRef](#)]
29. Xu, Y.L. *Wind Effects on Cable-Supported Bridges*; John Wiley & Sons: Hoboken, NJ, USA, 2013.
30. Caracoglia, L. Wind Effects on Structures: Modern Structural Design for Wind. *J. Struct. Eng.* **2021**, *147*, 07520001. [[CrossRef](#)]
31. Murea, C.M.; Tiba, D. Topological Optimization and Minimal Compliance in Linear Elasticity. *Evol. Equ. Control Theory* **2020**, *9*, 1115–1131. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.