Conceptual Robot Design For The Automated Layout of Building Structures By Integrating QFD And TRIZ

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Abstract

According to the increase in building size and lack of skilled laborers, layout operation has high demands on automation for productivity and quality improvement. With such a background, research has been recently undertaken to develop an automated layout system based on marking robots for structural work in Korea. Although there are several robot-based automation systems under development targeted at interior works, the system for structural work has different functional needs and technical requirements in designing the robots compared with the existing ones. Therefore, this study proposes a conceptual robot design for an automated layout of building structures, based on a systematic design process, by integrating quality function deployment (QFD) and the theory of creative problem solving (TRIZ). With the support of the approach, 11 user requirements and 16 relevant technical characteristics were derived and prioritized, and 15 creative ideas were derived to solve the technical contradictions. The selected design solution improves driving speed by separating driving and marking operations, and the two-wheeled steering drive system with a suspension device allows easier driving control in a narrow and uneven driving environment. The noncontact type of printer head also minimizes the complexity of the device and provides excellent performance in securing marking precision and quality in response to floor conditions. The results of this study will be used for the detailed design of the layout robot system, and the design process can be utilized for designing and evaluating other construction robots and automation systems.

1 Introduction

According to the increase in building size and irregularity and lack of skilled laborers, layout work has high demands on automation for enhancing productivity and quality. The layout work requires high accuracy and precision in surveying and marking for accurately constructing the shape and dimensions of the building frame. Traditional layout operations manually convert digital drawing information back through a tape measure in a conventional manner by layout workers. Thus, marking accuracy as well as worker proficiency can be significantly reduced by this process. In addition, the information in the layout process is not digitized, and the additional conversion process, such as creating layout drawings and inspection reports, result in lower productivity, loss of information in the conversion process, and failure to link to subsequent processes. Therefore, an automated layout system and digitalization for information linkage are considered essential to improve the precision and productivity of the layout operation.

In response to those demands, automation systems for layout operation have been developed mainly in two different ways: (1) robotic layout systems, in which a mobile robot localizes and performs marking work itself; and (2) laser projection systems, in which a projector displays the layout onto workspaces and then workers directly lay down along the projected lines. Because it is very important to secure accuracy of the location of marked or projected lines, both methods are being developed with the goal of securing marking error less than 3 mm. However, in the laser projection method, there are restrictions on the range of projection capabilities (up to 10 m) to ensure positional accuracy. In addition, in case of projector failure during operation, installation work in the area cannot proceed. Thus, the introduction of the robotic layout systems linked to surveying and inspection automation technologies is considered to be a more efficient approach.

Full-scale development for robotic layout systems has been carried out in the United States and Japan since the 2010s, and a few companies, such as Takenaka Corporation [1], Hitachi Plant Corporation [2], and Dusty Robotics [3], are currently conducting on-site or laboratory testing of prototypes. However, the systems have limitations on the applicable scope and environment for ensuring marking accuracy, which is targeted at the layout of interior works such as dry walls, access floors, and on finished floors with a certain level of flatness.

In Korea, research has been recently undertaken with the aim of developing an automated layout system for structural work. Compared to the existing systems, the robot system to be developed in this research should ensure precise marking and driving performance in response to poor working conditions such as rough floor conditions, sleeves, and rebars. This results in different functional needs and technical requirements in designing the robot system. Therefore, this study proposes a conceptual robot design for an automated layout of building structures based on a systematic design process. The lack of existing similar technologies requires the application of systematic design techniques for efficient system design. Thus, to derive an optimal design solution, this study used quality function deployment (QFD), a customer-centered product design support technique, integrated with the theory of creative problem solving (TRIZ) method.

2 Design Process By Integrating Qfd And Triz

QFD has advantages in designing and improving user-centered systems by converting user requirements into technical characteristics of products and quantifying their priorities. However, QFD does not fully consider the correlation between technology elements, and the focus is on the deployment of technology elements, making it difficult to generate problem-solving ideas by the scientific approach [4]. On the other hand, the TRIZ technique can be a useful tool to compensate for the shortcomings of QFD by allowing systematically creative problem solutions by considering the correlation of technical contradictions [5]. Thus, for efficient and practical design solutions for making robot systems, this study has applied a systematic design process by integrating QFD and TRIZ techniques, as shown in Fig. 1.

2.1 Conversion of customer requirements into technical characteristics using the QFD

2.1.1 Derive user requirements and their importance for marking robots

This study uses basic house of quality (HOQ) matrices in the QFD approach to convert qualitative user needs into quantitative technical characteristics. First, important user requirements for making robots for building structures are collected from users, including construction site managers in general and specialty contractors. The requirements are derived based on user interviews, relevant literature, and construction process analysis, and then the importance of the derived requirements is determined through a questionnaire from users.

2.1.2 Derive the technical characteristics based on quality requirements

Technical characteristics such as the shape, size, and weight of robots are derived by a group of experts. To develop proper technology elements, a high understanding of the target robot system is required. However, because there are currently no experts with developmental experience of the corresponding system, a task-force team from the research group for developing an automated layout system of building structures is established and technical characteristics are determined through the team meetings.

2.1.3 Prioritize technical elements based on correlations with user requirements

The correlation between the quality requirements and the technical characteristics is analyzed to identify which technical characteristics of the robot are important to reflect the user's requirements. This process also requires a high understanding of the system, so it is carried out through the same experts in the task-force team. The correlation is assessed with the values of 1, 3, and 9, which indicate possible, moderate, and strong correlations, respectively. Technical elements are prioritized by multiplying the correlation value with the importance of the corresponding requirements.

2.1.4 Analyze correlation between technical characteristics

Correlation between technical elements with high priority and other ones is analyzed. If there is a negative correlation between technical characteristics, it is converted into a contradiction problem.

2.2 Problem solving by inventive principles in TRIZ

2.2.1 Transform technical contradictions into engineering parameters

Each technical element with negative correlation is converted into a relevant one of 39 standard engineering parameters proposed by Altshuller [6]. To solve a technical contradiction, the transformed parameters are applied to the contradiction matrix in TRIZ. In the matrix, the parameters to be improved are placed in rows and the parameters to worsen are placed in columns, and the inventive principles are provided on the intersections where the two parameters meet.

2.2.2 Derive problem-solving ideas based on the inventive principles

The inventive principles in TRIZ provide conceptual solutions that are derived through patents and technology cases that resolve existing contradictions. This facilitates generating effective ideas on a specific problem, enabling simultaneous satisfaction of conflicting parameters. In this study, based on the relative inventive principles, after collecting the ideas provided by each member of the task-force team, they are organized through several team meetings.

2.2.3 Create and compare design solutions for marking robot

The ideas for subsystems are combined to create design alternatives for the marking robot system. A quantitative evaluation is performed to select an optimal design solution among the alternatives. In this study, a comparative assessment among the derived alternatives is conducted because it is difficult to find existing comparable systems. The extent to which each alternative satisfies the related key requirements is evaluated on a five-point scale, multiplied by the importance of the requirements, and determined as the optimal solution with a greater total sum.

3 Design Development Of Construction Layout Robot Based On Qfd And Triz Integration

3.1 Customer requirements

To derive the customer requirements, we conducted relevant literature reviews and a traditional layout process analysis through on-site observation. There were 13 factors first derived from this process, and a total of 11 requirements were finally defined as required quality through feedback from the site managers in general contractors and specialty contractors for structural work.

After identifying the requirements, a questionnaire was conducted to evaluate the degree of importance for each factor. Through an online survey that took about 10 days, 49 completed questionnaires were collected targeted at construction site managers. A total of 42 questionnaires were used for analysis; seven of the completed questionnaires were judged to be unreliable. On average, the respondents had about 18 years of experience in building construction works (Table 1), and most respondents answered that there was a need for automating layout work (90.6% of respondents checked more than 3 points (normal) on a 5-point scale).

Table 2 shows the importance levels for the CRs that converted the average value of each requirement surveyed on a 5-point scale into 100 points. The most important requirement was to secure marking accuracy within the tolerance (CR1), considering the purpose of the layout operation. Next, it was considered important to drive performance coping with site conditions (CR3), keep constant marking quality (CR4), and easy operation and maintenance (CR11). This is believed to be because the robot system in this study should drive and mark in poor ground and working conditions, unlike the systems for interior layout on finished floors.

3.2 Technical characteristics and correlations between CRs and TCs

Related technical characteristics (TCs) were derived through analyzing the 11 requirements. TCs were suggested by the members of the research group based on their knowledge, experience, and relevant documents because they have a high understanding of the operational processes. The robot system can be largely divided into driving, marking, and power supply units, and 16 technical factors required for each unit and robot design were derived to satisfy the customer demands.

Next, the correlation between CRs and TCs was derived through a group meeting of the task-force team to prioritize impacts of the TCs on achieving customer needs. The strength of the relationship was assessed with values of 1 (possibly correlated), 3 (moderately correlated), and 9 (strongly correlated), as proposed by Cohen [7]. As shown in Table 3, movement control (TC6), marking control (TC11), and sensing (TC12) devices have correlations with the largest number of CRs. Movement control and sensing devices have high correlations with the demands of CR3, 8, and 9, while marking control devices have high correlations with CR1, 2, and 4.

To quantify the importance of each technical factor, absolute weight (AW) and relative weight (RW) were calculated by equations 1 and 2, respectively. From the AWs and RWs, the prioritized TCs are concerned with component control and sensing. Movement and marking control and sensing devices reflect about 31.7% in the design of the layout robot. Next, important technical factors were shown in the order of ink supply device (TC10), robot weight (TC3), and marking speed (TC9). The presented six factors contribute more than 50% of the total RW and thus were selected as key TCs to propose innovative solutions while meeting customer demands.

$$\text{AW} = \sum(\textit{Importance level} \times \textit{Correlation value}) \qquad (1)$$

$$\text{RW} = \frac{\textit{AW of corresponding factor}}{\sum \textit{AW with each technical factor}} \times 100 \qquad (2)$$

3.3 Contradiction analysis

Technical correlations in the roof of the HOQ were derived from the task-force team of the research group to identify design bottlenecks. In this study, the interaction between TCs was represented as symbols + and –, indicating positive and negative correlations, respectively (Fig. 2).

Highly important technical factors, including TC6, TC11, and TC12, mainly showed negative correlations with speed (TC4, TC9), weight (TC3), size (TC2), and/or battery capacity (TC15). The negatively correlated TCs are described as technical contradictions reflecting the requirements, as follows: (C1, C2) For easy and accurate control while coping with uneven ground conditions, movement and marking speed should be slowed; (C3) To ensure precise marking and sensing performance, the complexity of equipment increases, resulting in an increase in battery consumption; (C4) For various types of marking while maintaining marking quality, the volume of the robot system should be increased.

Among six technical factors, the factors with technical contradictions between them were set as the improving factor for the characteristics with higher weights. In addition, battery capacity can be improved while reducing the complexity of the system, which is excluded from establishing contradictions. The presented four contradictions should be transformed into technical parameters in TRIZ. The improving and worsening features were converted into highly relevant parameters to use inventive principles in the contradiction matrix, as shown in Table 4. Each solution principle number in Table 4 indicates one of the 40 inventive principles proposed by Altshuller [6].

3.4 Problem-solving ideas and design alternatives based on the inventive principle

Among the invention principles corresponding to each contradiction, one to two invention principles that fit the design of an automated marking robot were used to derive problem-solving ideas. The ideas were derived through analogy thinking by referring to the conceptual solutions provided by inventive principles. For example, to resolve the C3 contradiction, a conceptual solution using the principle of “prior action (10)” was derived: “Place objects in advance so that they can go into action immediately from the most convenient location.” With reference to the solution, the idea of “replacing sensing devices for precise measurement and control by inputting the location of obstacles in the drawing in advance” was derived. The problem-solving ideas for other contradictions were derived by the same principle and process, as shown in Table 5.

The presented ideas were organized and integrated to derive design alternatives for marking robots. First, they can be distinguished by the driving and marking operation method. The first method is to separate the robot’s driving and marking (idea A). The robot performs the marking operation while it is stationary, increasing the speed of movement by decreasing the positional precision when operating the robot. On the other hand, the second method is to enhance the overall speed of work by performing marking operations while the robot is running (idea D). This approach requires a relatively low speed of movement of the robot and minimizing marking lines to secure marking accuracy.

Next, the ideas are classified by the marking method. First, the printer head of the noncontact type from the floor integrated with ink supply unit moving on a single axis (ideas I and O) can be applied. This can print various types of marks including lines, texts, and symbols while requiring a supplementary device to maintain a certain distance from the floor surface. Second, a method of drawing a line of constant length through marking the head of a bar type (idea J) can be applied. These types of marking methods are suitable for operating the robot separately from marking and driving. On the other hand, in the operation method of marking and driving simultaneously, a point-by-point marking method such as a cross (+) shape (idea H) can be applied instead of lines at regular intervals to secure precision in marking. Regardless of the marking method, the marking head shall be exposed to the outside of the robot body to perform marking adjacent to rebars protruding over the floor and installed on one side of the robot body for easy control (idea C). In addition, for driving wheels, the two-wheeled steering drive system with suspension devices (ideas B and E) and one- or two-wheel caster is adopted for efficient movement and rotation in narrow spaces as well as improvement of driving performance on uneven floors.

As a result, three design alternatives are derived through the combination of robot operation and marking methods, as shown in Table 6. Regardless of design alternatives, the robot's position and orientation can be accurately calculated through a movable prism target installed on the top of the robot body and tracking of the total station (idea G). In addition, the location information of fixed obstacles on the robot's driving path can be inputted in the drawing in advance (idea K), and the avoidance path can be generated to replace the expensive sensing device for precise recognition.

3.5 Evaluation of alternatives and selection of optimal robot design

A quantitative assessment was conducted to select an optimal design solution among the three alternatives. In general, the usefulness of solutions is assessed through comparisons with existing systems that are subject to improvement. However, this study used comparative evaluation among the alternatives because it is not intended to improve existing systems. Six evaluation criteria were first set based on the user requirements that are highly correlated with the key TCs and of high importance, and the weight of each criterion was calculated from the importance value of the requirements being targeted. The degree to which each alternative meets the established evaluation criteria was derived on a five-point scale through consultation between the task-force team members. The final performance score of each alternative was calculated by multiplying the weight by the corresponding score of each criterion and then adding it together.

As a result of the evaluation, the first alternative to marking using the noncontact type of printer head while stationary was selected as the optimal design solution with a score of 4.17 (Table 7). The third alternative was best evaluated in terms of duration reduction on marking work, but the complexity of algorithms for position calculation and control of the robot increases and additional devices are expected to be needed to secure marking precision. In the case of the second alternative, it is possible to mark only a line shape of a certain length by stamping the bar type marking head. Thus, the performance in terms of the variety and quality of the marking was assessed to be relatively poor.

It was evaluated that with the first alternative, it was possible to secure excellent performance in terms of marking precision, which is the most important requirement, as the printer head moves and marks uniaxially along with an auxiliary device to maintain a certain distance from the floor in a stationary state. In addition, unlike other alternatives, it was evaluated excellently in terms of being able to mark various types of lines, symbols, and texts. The complexity is minimized by configuring the device to enable marking through direct jetting from the ink cartridge without a separate supply unit, and it is possible to secure the diversity of marking colors more easily by allowing only the cartridge to be additionally attached depending on the situation. Figs 3 and 4 show the concept design of the robot and operation process based on the first alternative, respectively.

4 Findings And Discussion

This study was conducted to derive an appropriate design for systems that do not yet exist commercially available and that have different application environments from similar systems under development. To this end, more systematic design support techniques have been utilized. First, the QFD provided a systematic and quantified approach in deriving the engineering characteristics to satisfy user requirements for developing the marking robot for building structures. A total of 11 requirements were derived, and high demand for marking accuracy and environmental responsiveness was identified. On the other hand, the need for the marking of various colors or types was relatively low because of the nature of the structural work. To meet these user requirements, a total of 16 TCs were derived, and the main factors such as control and sensing, weight, and marking speed were identified through correlation analysis.

Through the support of the invention principles from the contradiction between TCs derived through the QFD, the TRIZ was able to present the direction of thinking in the process of idea development and derive better solutions. The robot system to be developed has a high correlation among the engineering factors as many technologies shall be adopted on one platform. There were also many technical contradictions because it requires higher productivity than the existing method in a poor working environment. Thus, this study derived creative ideas to address contradictions between key engineering factors more effectively through the support of inventive principles in the TRIZ. In this study, a total of 15 ideas were derived to solve the four technical contradictions, and three design alternatives were suggested through the integration of ideas.

In addition, this study is meaningful in analyzing the effectiveness of design solutions that can meet key user requirements by setting them as evaluation criteria and selecting alternatives through quantitative weighing. The selected concept design will be able to improve driving speed by separating driving and marking operations, and the two-wheeled steering drive system with a suspension device will allow easier driving control in a narrow and uneven driving environment. The noncontact type of printer head, which can be sprayed directly from ink cartridges, will minimize the complexity of the device and provide excellent performance in securing marking precision and quality.

In this study, robot design focuses on presenting solutions through contradictory resolutions for key TCs and thus meeting key requirements. Therefore, it is required to create additional solutions to meet user needs that are not sufficiently considered in this study, such as securing waterproof and dustproof performance, and economic feasibility for the practical use of robots.

5 Conclusions

This study proposed a conceptual robot design for the automated layout work of building structures. A systematic methodology incorporating QFD and TRIZ was used for optimal robot design. The QFD process provided a systematic tool for deriving and prioritizing user needs and related TCs and the TRIZ enabled product conception to resolve technical contradictions and achieve optimal performance.

The design solutions focused on meeting the key requirements such as environmental responsiveness, productivity, and marking accuracy and quality. The selected solution enables a smoother driving performance in narrow and uneven driving environments and improves driving speed through the separation of marking work. The marking part structure minimizes the complexity of the device and ensures marking quality and precision in response to floor conditions. The results of this study will be used for a detailed design of the layout robot system, and other QFD deployments can be applied to define requirements for parts design deployment. In addition, the design process presented in this study can be utilized for design and quantitative evaluation of other construction robots and automation systems.

Although this study focused on conceptual design from a hardware perspective, performance in software aspects such as robot control and error correction algorithms shall be supported to achieve targeted robot performance. In addition, technology development is required to automate the overall layout process on an integrated platform such as automated modeling for layout drawing, moving path optimization, and automated inspection. Future research plans aim to develop and integrate the aforementioned technologies along with the development of the robotic hardware.

Declarations

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Conflicts of interest

The authors declare no conflict of interest.

Availability of data and material

All data generated or analyzed during this study are included in this article.

Code availability

Not applicable

Ethics approval

Not applicable

Consent to participate

Consent to participate in this study was obtained from all the authors.

Consent for publication

Consent for publication was obtained from all the authors.

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Tables

Table 1 Information on survey respondents

Respondents	Number of respondents	Average experience (years)
Construction manager for general contractor	30	17.5
Site manager for specialty contractor for structural work	5	16.6
Supervisor	1	25
Architectural designer	2	18
Client	1	18
Structural engineer	1	18
Professor	2	16.5
Total	42	17.6

Table 2 Customer requirements and importance level

ID	Requirements	Importance level	Rank
CR1	Ensuring accurate marking within tolerance	97.14	1
CR2	Reducing working duration than labor's	83.33	5
CR3	Driving performance coping with site conditions	87.14	2
CR4	Constant marking quality	85.24	3
CR5	Different types of marking lines	68.57	11
CR6	Ensuring power supply capacity during marking	77.62	9
CR7	Securing water- and dustproof performance	82.38	7
CR8	Obstacle recognition and avoidance	83.33	5
CR9	Real-time progress and status check	79.52	8
CR10	Easy transport and storage	77.62	9
CR11	Easy operation and maintenance	85.24	3

Table 3 Correlations between CRs and TCs

TCs	Robot shape	Robot size	Robot weight	Movement speed	Driving device	Movement control device	Shape of marking device	Location of marking device	Marking speed	Ink supply device	Marking control device	Sensing device	Robot durability
	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13
CRs													
CR1	3	1			1	3	3	3	9	3	9	3	
CR2	1	1	1	9	3	3			9	3	9	3	
CR3	3	1	3	3	9	9						9	3
CR4				3	3	1	9	9	9	9	9		
CR5							9			9	1		
CR6		3	9	3	1	1			1	1	1	1	
CR7	3	1			1		1	1					9
CR8	3	1		3	1	9					1	9	
CR9				1		9					1	9	
CR10	9	9	9										1
CR11		9	9		3	9				9	9	9	9
AW	1832	2132	2509	1829	1886	3721	1758	1141	2469	2770	3468	3636	1848
RW	5.35	6.23	7.33	5.35	5.51	10.88	5.14	3.33	7.22	8.10	10.14	10.63	5.40
Rank	10	7	5	11	8	1	12	14	6	4	3	2	9

Table 4 Technical contradictions and corresponding parameters and inventive principle in TRIZ

Contradiction	Improving factor	Improving parameter	Worsening factor	Worsening parameter	Solution principle number
C1	TC6, TC11	37. Complexity of control	TC4, TC9	9. Velocity	3,4,16,35
C2		28. Measurement accuracy			28,13,32,24
C3	TC6, TC11, TC12	28. Measurement accuracy	TC3	36. Complexity of subsystem	27,35,10,34
C4	TC10	33. Facility in subsystem operation	TC2	7. Volume	1,16,35,15

Table 5 Problem-solving ideas based on inventive principles

Contradiction	Inventive principle	Conceptual solution	Problem-solving idea
C1	3. Local quality	Different parts of an object should carry out different functions. Each part of an object should be placed under conditions that are most favorable for its operation.	A. Separate robot movement and marking operations to reduce the robot's position accuracy level while increasing the robot's moving speed. B. Use a two-wheeled steering drive system to increase the efficiency of driving and control.
	4. Asymmetry	Asymmetrically built conjunctions, handles	C. Install the marking section on one side to limit movement in one direction, reducing movement control for marking and increasing the speed of movement of the robot.
	16. Partial or Excessive Action	If it is difficult to obtain 100% of a desired effect, achieve more or less of the desired effect.	D. Reduce the moving speed, but increase the overall speed of work by simultaneously driving and marking and minimizing the marking line printing.
	35. Transform of properties	Change the degree of flexibility.	E. Install a suspension on the wheel to absorb irregularities on the floor. F. Install a small wheel with a spring force beside the marking head to be kept a constant distance from the floor surface.
C2	28. Replacement of the mechanical system	Replace a mechanical system with an optical, acoustical, thermal, or olfactory system.	G. Install movable prism target for measuring positions and orientations of the robot.
	13. Do it in reverse	Instead of the direct action dictated by a problem, implement an opposite action. Make the movable part of an object, or outside environment, stationary — and stationary part movable.	H. Reverse the required continuous line and switch to point-by-point marking. The speed of the robot is improved by reducing the control of marking and movement. I. Make the moving part for controlling the marking device to a single axis and move the marking head itself to maintain accuracy and improve the control speed.
C3	35. Transform of properties	Change the physical state of the system.	J. Remove separate supply nozzles with the marking method of bar type. It can minimize system complexity while increasing control efficiency.
	10. Prior action	Place objects in advance so that they can go into action immediately from the most convenient location.	K. Input the location information of obstacles in the drawing in advance to replace expensive sensing devices for precise measurement and control. L. Remove any movable obstacles and debris from the robot's travel path in advance.
C4	1. Segmentation	Make an object sectional (for easy assembly or disassembly).	M. Easily adjust the number of printer heads and nozzles as necessary.
	16. Partial or excessive action	If it is difficult to obtain 100% of a desired effect, achieve more or less of the desired effect.	N. Use one color for marking to reduce the volume of the ink supply unit.
	15. Dynamicity	Make it interchangeable.	O. Unify ink supply and marking unit. The marking method printed directly from the ink cartridge can be used.

Table 6 Design alternatives through idea combination

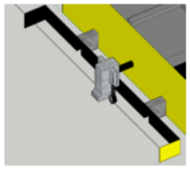
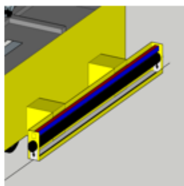
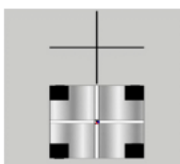
Alternatives	Classification	Idea	Description	Function
Alt. 1	Operation method	A	Perform marking work while the robot is stationary.	Increase the moving speed and marking accuracy.
	Marking method	I, O	Use the printer head of noncontact type integrated with an ink supply unit. 	Enhance marking quality and diversity.
Alt. 2	Operation method	A	Perform marking work while the robot is stationary.	Increase the moving speed and marking accuracy.
	Marking method	J	Use marking head of a bar type. 	Minimize the complexity of the system.
Alt. 3	Operation method	D	Perform marking work while the robot is running.	Enhance the overall work speed.
	Marking method	H	Use point-by-point marking method such as a cross(+) shape. 	Secure marking precision and easy control.

Table 7 Comparative evaluation of alternatives

Evaluation criteria	Weight	Alt.1	Alt.2	Alt.3
Precision	0.20	5	3	2
Working time	0.16	3	2	5
Quality	0.17	4	2	4
Adaptability	0.17	5	2	4
Operability	0.17	3	3	4
Marking diversity	0.13	5	1	2
Sum		4.17	2.24	3.5

Figures

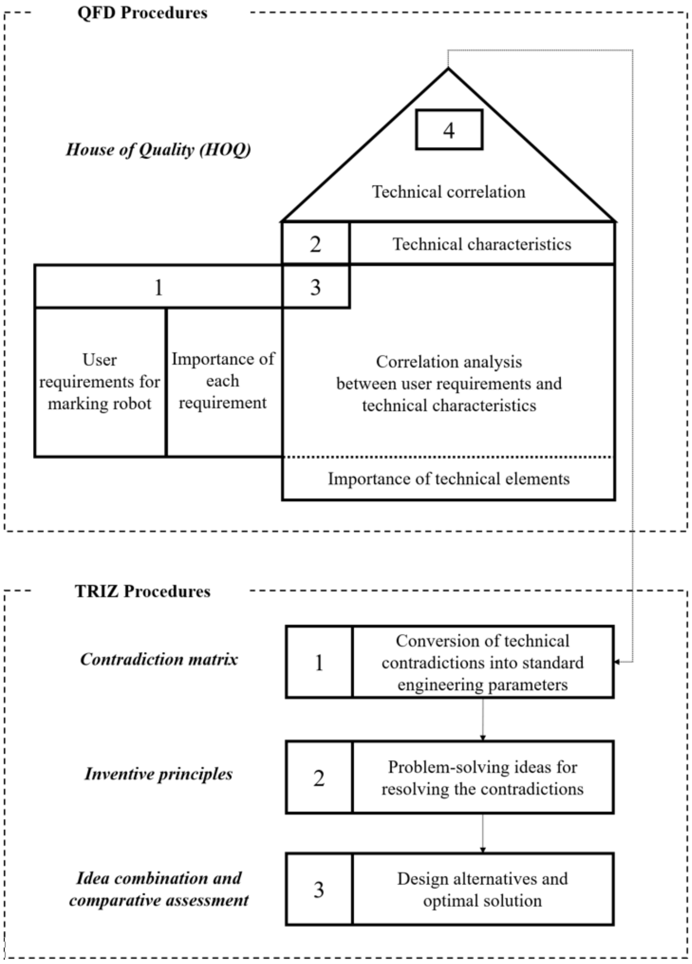


Figure 1

Design process by integrating QFD and TRIZ

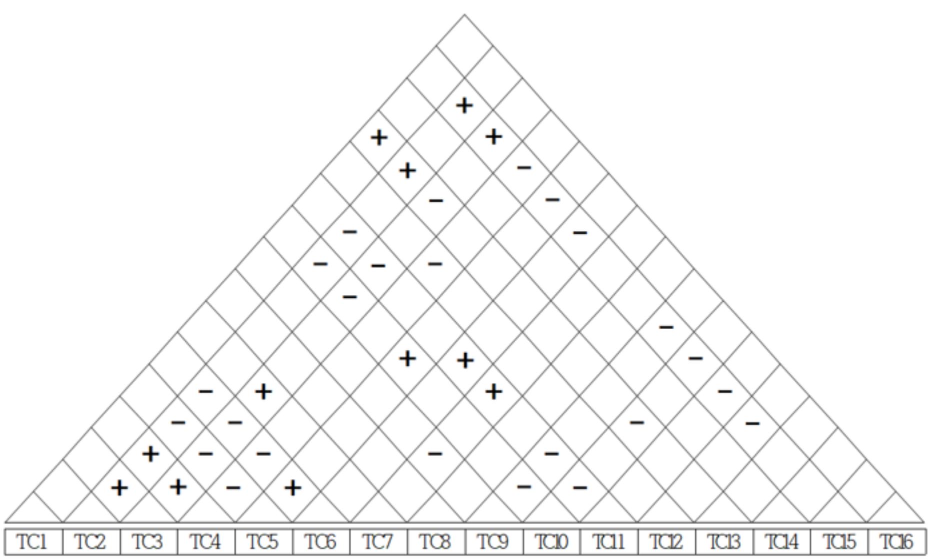


Figure 2

Technical correlations

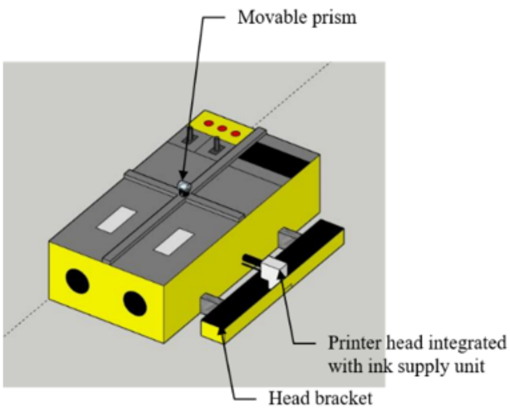


Figure 3

Concept design of the layout robot

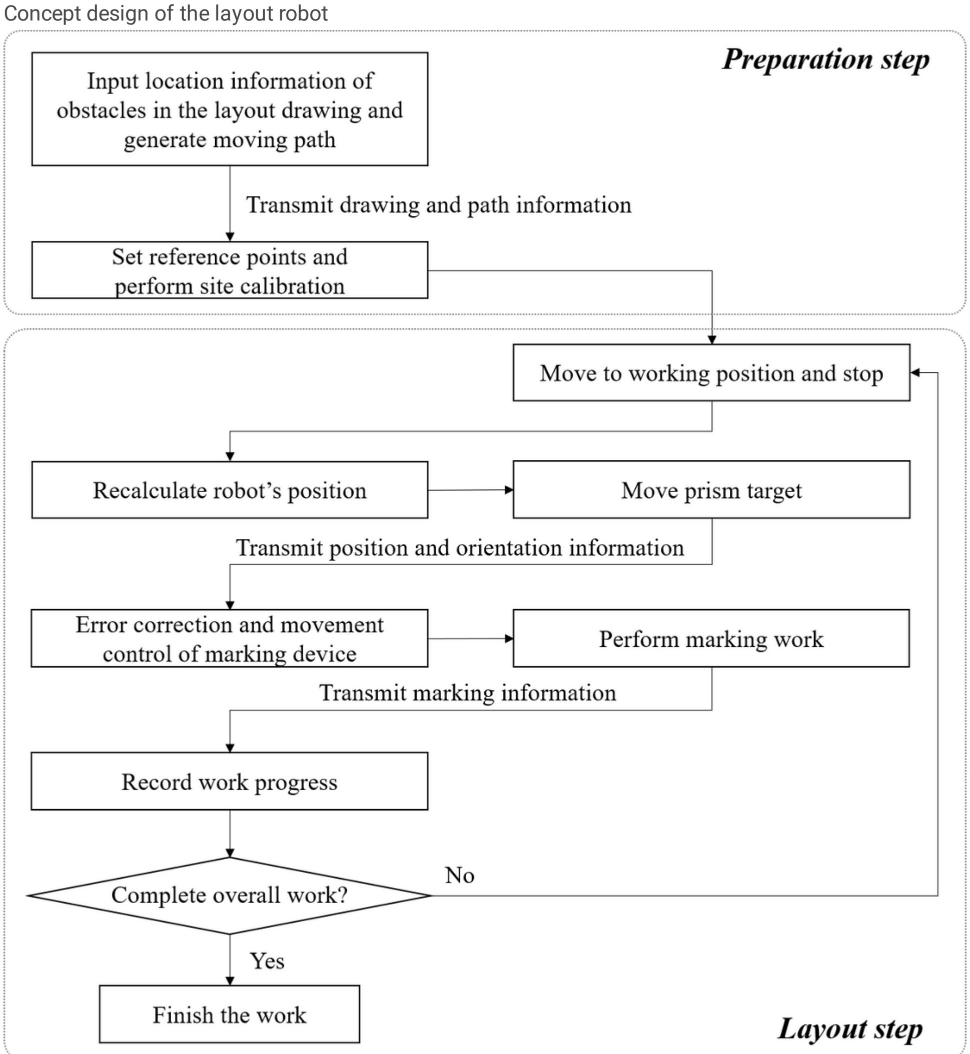


Figure 4

Preparation and layout operation process