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DESIGN OF A FIREPROOFING SPRAY ROBOT BASED ON QUALITY FUNCTION DEPLOYMENT

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Abstract

Fireproofing spray works are critical for protecting the structural integrity of steel frames during fires, yet they present challenges related to worker safety and construction quality. While robotic automation has been explored to mitigate these risks, most existing robotic systems have focused on technical feasibility, overlooking user-centered design. This study applies the Quality Function Deployment (QFD) methodology to systematically incorporate user requirements into the conceptual design of a fireproofing spray robot. Twelve customer requirements were identified through expert interviews and field observations, and fifteen technical characteristics were derived through functional decomposition. A correlation and contradiction analysis was conducted to examine interdependencies and trade-offs among these characteristics. Based on the results, three design alternatives were proposed: a lightweight and modular structure, a sensor optimization-focused configuration, and an integrated material feeder system. The study demonstrates that applying QFD enables the alignment of technical specifications with practical field needs, thereby enhancing the robot's applicability in construction environments and supporting future commercialization.

Keywords: construction automation, fireproofing spray robot, quality function deployment

1. Introduction

In building construction, fireproofing spray works are critical for protecting the load-bearing capacity of steel structures during fires. As stated in NFPA and NIST guidelines, steel can lose up to 50% of its strength at temperatures exceeding 550°C [1]. Under fire-induced high temperatures, the fireproofing material expands rapidly through intumescence, generating a thick, porous insulating layer that shields the steel structure from thermal damage.

Traditionally, in fireproof spraying work, the operator carries a spray gun connected to a material supply equipment and rides a scissor lift or crane to an elevated position to perform the spraying. This existing work method has inherent limitations, including the potential for fall accidents, operator exposure to dispersed fireproofing materials, and a reliance on worker skill for consistent work quality [2][3].

To address these challenges, robotic systems have been introduced to automate fireproofing spray work. Ikeda et al. [4], developed fireproofing spray robot focused on automating movement, alignment, and spraying. However, the applicability of their study is limited in construction site because it overlooks broader operational needs such as quality inspection and the robot's potential for multi-task deployment [5].

To successfully deploy robotic systems at construction sites, it is crucial not only to demonstrate task-level feasibility but also to design systems with the broader goal of solving real-world site problems and supporting the overall construction workflow. Moreover, as the technological maturity of fireproofing spray robots improves, new demands emerge for the integration of user-centric considerations into system design. For robots to be viable for commercial deployment, it is essential not only to verify technical feasibility but also to systematically incorporate field-level user requirements—such as

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operational convenience, adaptability to varying site conditions, and maintenance efficiency—into the development process.

To incorporate these user requirements into the development process, this study adopts the Quality Function Deployment (QFD) methodology. Through QFD, customer requirements are systematically collected, technical characteristics are derived and analyzed, and their priorities are established. Based on these priorities, complementary and conflicting relationships among technical characteristics are examined to propose design alternatives. The proposed fireproofing spray robot designs aim to facilitate practical application at construction sites and ultimately support the successful commercialization of robotic systems.

2. Literature review

While robotic systems have been proposed to automate fireproofing spray work, previous studies have largely focused on validating technical feasibility in isolated tasks. For example, Ikeda et al. [4] developed a semi-autonomous robot equipped with a mobile platform, lifting mechanism, and a six-axis industrial arm to perform fireproofing spray works. However, their system was designed with a narrow focus—limited to movement, alignment, and spraying functions—without considering modularization, upstream and downstream processes essential to actual job completion, such as identifying spray zones, detecting coverage gaps, or confirming completion quality. This task-oriented perspective neglects the complex sequential and variable workflows of construction sites, where operational continuity and flexibility are critical. Therefore, despite technical success, the system lacks readiness for real-world deployment due to the absence of user-centered design principles.

Meanwhile, Pasawang et al. [7] demonstrated a more holistic approach by applying QFD at the conceptual design stage of an autonomous underwater robot. By translating user needs into prioritized technical specifications early in the process, they ensured the system was not only technically sound but also aligned with practical user constraints, such as ease of operation, robustness under field variability, and maintainability. Their methodology highlights how structured requirement analysis can bridge the gap between technical feasibility and operational usability—an insight directly applicable to fireproofing robot design.

Further reinforcing this perspective, Eleftheriadis et al. [8] integrated QFD with Building Information Modeling (BIM) to incorporate multi-stakeholder needs into early-stage structural design. Though not robotics-focused, their work underscores the value of participatory design frameworks in construction contexts. Similarly, Lee et al. [9] introduced a stochastic QFD model to improve decision-making under uncertainty in contractor evaluation. While service-oriented, probabilistic modeling offers methodological insight for dealing with the variability inherent in construction sites.

These prior works collectively suggest that QFD enables more robust and context-aware system design by prioritizing stakeholder input. However, its application to construction robotics remains limited, particularly for fireproofing tasks. This study aims to fill this gap by applying QFD to translate on-site user requirements into structured technical characteristics, thus improving the applicability, usability, and commercial readiness of robotic systems for fireproofing spray work.

3. Methodology

3.1. Research Framework Overview

This study employs QFD methodology to systematically integrate user needs into the design of fireproofing spray robots. QFD was selected because it provides a structured approach to translate field-level customer requirements into prioritized technical characteristics during the early conceptual design phase. This method helps bridge the gap between technical feasibility and real-world commercial applicability, ensuring that the final system aligns with both operational demands and user expectations.

3.2. Process of Deriving Customer Requirements

To capture comprehensive customer requirements (CRs), a multi-stage approach was adopted. First, relevant fireproofing specifications, academic studies, and real-world spraying processes were reviewed. Based on this initial analysis, 19 preliminary requirements were identified. Subsequently, expert interviews and feedback from robot developers and construction automation researchers refined the list to 12 core customer requirements. The importance of each CR was quantified through a survey using a 5-point Likert scale, with responses collected from construction automation experts and experienced field workers.

3.3. Process of Deriving Technical Characteristics

Technical characteristics (TCs) necessary to fulfill the identified customer requirements were derived through expert workshops. Drawing upon field experience and prior research in construction automation, 15 TCs were extracted, focusing on four main subsystems: mobility, lifting, supply, and operation. Experts evaluated the functional relationships between CRs and TCs, ensuring that each technical element was relevant to practical deployment conditions.

3.4. Correlation and Contradiction Analysis

A correlation matrix was constructed to assess the degree of relationship between CRs and TCs. Each correlation was rated on a standardized scale (9: strong, 3: moderate, 1: weak). In addition, interrelationships among TCs were analyzed to identify potential synergies (positive correlations) and trade-offs (negative correlations). This analysis provided a structured foundation for balancing conflicting technical requirements during robot system design.

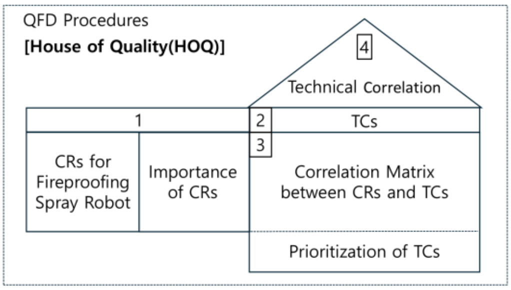

Figure 1. Structure of the House of Quality (HOQ) used for QFD-based design of a fireproofing spray robot.

3.5. Development of Design Alternatives

Based on the prioritization of technical characteristics and the identified synergies and conflicts, three design alternatives were formulated. Each alternative strategically addresses key trade-offs and operational priorities identified through the QFD process, offering tailored solutions for fireproofing spray robot development depending on different project requirements.

4. Designing a robot to be refractory through QFD process application

4.1. Identification and Prioritization of Customer Requirements (CRs)

To derive the customer requirements (CRs) for the fireproofing spray robot, a preliminary investigation was conducted by reviewing specification documents and academic literature related to fireproofing works, and by analysing actual spray-applied fireproofing tasks on construction sites. Additionally, expert workshops and discussions were conducted to explore how robotic systems could perform these tasks in practice.

Initially, 19 requirement elements were identified. These were refined into 12 core customer requirements through iterative feedback from robot developers and researchers specializing in construction automation. Based on these finalized CRs, a structured survey was conducted to assess the relative importance of each requirement.

The survey was conducted over a 10-day period and yielded responses from 19 experts, including construction automation researchers and experienced field workers. On average, the researchers had over three years of experience in the domain, while the field workers had more than 20 years of hands-on experience in fireproofing works.

Table 1. Information on survey respondents

Responders	Number of respondents	Average experience
Construction automation researcher	10	3
Professor	4	5
Construction manager	5	20
Total	19	3

As shown in Table 2, the survey results indicate that all respondents rated the importance of a fireproofing spray robot above 3.0 on a 5-point Likert scale, reflecting a general agreement on the necessity of such a system. The table presents the normalized importance values of each customer requirement (CR) on a 100-point scale, allowing for a clear comparison of their relative importance.

Among the identified customer requirements, CR2 (Precise thickness control) received the highest importance score. This requirement emphasizes the need for maintaining consistent spray thickness, which is essential for ensuring the protective performance of fireproofing. Deviations in thickness can reduce fire resistance, highlighting the importance of precise application.

CR12 (Applicability across multiple work tasks) was also rated highly, indicating a preference for a versatile robot capable of performing various construction tasks beyond fireproofing. This versatility helps justify the initial cost of the robot by enhancing its potential applications.

CR1 (Continuous, clog-free spraying) was identified as another important requirement. This feature ensures uninterrupted operation, preventing delays caused by clogged hoses, which can negatively impact the quality of fireproofing.

Finally, CR6 (Operation in irregular and elevated areas) was recognized as significant, reflecting the need for the robot to function in complex and elevated environments where manual application is challenging.

In summary, the survey results suggest that the design of the fireproofing spray robot should focus on precise thickness control, multi-functionality, operational continuity, and adaptability to various work conditions. These priorities enhance the robot's practical utility and potential for wider application.

Table 2. Customer requirements and importance level

ID	Requirements	Importance level	Rank
CR1	Continuous, clog-free spraying	88.89	3
CR2	Precise thickness control	93.33	1
CR3	Real-time spray quality correction	82.22	6
CR4	Multi-material spray compatibility	57.78	12
CR5	Overspray reduction	66.67	9
CR6	Work in irregular and elevated areas	86.67	4
CR7	Minimization of human intervention	80.00	7
CR8	Navigation in variable conditions	60.00	11
CR9	Easy transport, assembly, maintenance	64.44	10
CR10	Emergency response capability	77.78	8
CR11	Shorter or comparable operation time	84.44	5
CR12	Applicability across multiple work tasks	91.11	2

4.2. Derivation of Technical Characteristics and CR–TC Correlation Analysis

These technical characteristics were identified based on the knowledge, experience, and internal analysis of the research team specializing in construction automation. The robot system was categorized into four functional modules—mobility, lifting, supply, and spray—each associated with distinct technical features to fulfill the CRs. A correlation matrix was constructed to evaluate the strength of relationship between CRs and TCs, following Cohen's scale (1 = weak, 3 = moderate, 9 = strong), which is widely applied in QFD research for qualitative impact assessment.

As shown in Table 3, TC6, TC9, and TC1 received high relative weights, highlighting the importance of perception and control in ensuring consistent and autonomous spraying.

Table 3. Correlations between CRs and TCs

TCs	TC1	TC2	TC3	TC4	TC5	TC6	TC7
CRs	Robot shape	Robot size	Robot weight	Mobile base load capacity	Locomotion method	Spray control method	Mobility sensors type
CR1	3.00					9.00	
CR2						9.00	
CR3	1.00					9.00	
CR4	1.00	3.00		1.00		3.00	
CR5						9.00	
CR6	9.00	1.00		9.00	3.00		1.00
CR7	3.00			1.00	3.00	3.00	9.00
CR8	1.00		3.00	9.00	9.00		9.00
CR9	9.00	9.00	9.00	3.00	1.00	1.00	1.00
CR10	1.00		1.00	3.00	9.00	3.00	9.00
CR11	3.00	1.00	1.00	3.00	3.00	3.00	3.00
CR12	3.00	3.00		1.00	1.00	3.00	
AW	2611.11	1124.44	928.89	2222.22	2142.22	4157.78	2384.44
RW	5.17	2.23	1.84	4.40	4.24	8.23	4.72
Rank	3	9	10	5	6	1	4

TCs	TC8	TC9	TC10	TC11	TC12	TC13	TC14	TC15
CRs	Mobility sensor placement	Perception sensors type	Perception sensor placement	Material feeder shape	Material feeder size	Material feeder weight	Material feeder transport method	Power supply method
CR1		9.00	1.00					
CR2		9.00	1.00			1.00		
CR3		9.00	3.00					
CR4		3.00			1.00	1.00		
CR5	1.00	3.00						
CR6								
CR7	3.00	3.00	1.00			1.00		
CR8	3.00							
CR9		1.00		3.00	3.00	3.00	9.00	3.00
CR10	9.00	3.00						9.00
CR11		3.00					1.00	3.00
CR12		3.00	1.00	1.00	1.00	1.00	3.00	
AW	1186.67	3757.78	573.33	257.78	315.56	488.89	864.44	1166.67
RW	2.35	7.44	1.13	0.51	0.62	0.97	1.71	2.31
Rank	7	2	12	15	14	13	11	8

4.3. Correlation Analysis among Technical Characteristics

The upper matrix (roof) of the House of Quality (HOQ) was developed based on qualitative correlation analysis among the technical characteristics (TCs), aiming to identify complementary and conflicting relationships that affect robot design. A positive correlation between TCs—indicating mutual reinforcement—was marked with a "+" symbol, while a negative correlation—representing a trade-off or interference—was marked with a "–" symbol (Figure 2).

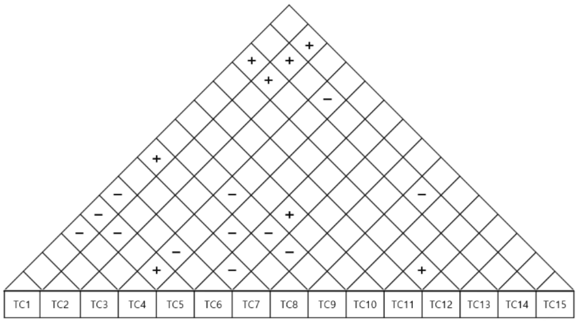

Figure 2. Technical correlations matrix

Based on the Roof analysis, among the 105 possible combinations derived from the 15 TCs, the key technical characteristics (TC6 and TC9), corresponding to the top 10% of Relative Weights (RW), were identified. These key TCs appeared repeatedly across multiple CR rows and were marked as contradictions (' - ') when conflicting interactions occurred. From this analysis, four contradiction pairs (C1–C4) were derived, representing critical design conflicts, such as sensor contamination, lift tilt, narrow passage width, and weight–precision control. The primary technical characteristics identified include TC6 (Spray control method), TC9 (Perception sensor type), TC1 (Robot shape), TC7 (Mobility sensor type), TC4 (Mobile base load capacity), and TC5 (Locomotion method). Through a mutual analysis of these characteristics, significant negative correlations were observed among certain TCs. These negative correlations indicate technical contradictions, which arise when attempting to fulfill conflicting customer requirements. The representative contradictions among these technical characteristics are as follows.

- C1(TC6 ↔ TC7, TC9) - Sensor Placement and Spray Control

  For optimized spray control, it is crucial that the sensors mounted on the robot are free from occlusions. This typically requires positioning the sensors in locations that are close to the spraying surface, ensuring accurate monitoring of the spray process. However, placing sensors in such positions increases the risk of them being contaminated by refractory spray material, which may splash during work. In particular, sensors such as cameras may experience reduced visibility due to material buildup. To mitigate this, it is essential to incorporate protective measures, such as using transparent covers with self-cleaning capabilities or adjusting sensor positions to minimize exposure without compromising their functionality.

- C2(TC4 ↔ TC14) - Payload Management and Feeder Configuration

  The payload of a robot is defined as the maximum weight it can safely support while maintaining precise work. In the case of a fireproofing spray robot, the feeder containing refractory spray material directly affects the robot's payload. As the material is consumed during operation, the weight of the robot changes dynamically. To maintain stability, the payload must be calculated based on the fully loaded feeder, which represents the worst-case scenario. However, increasing the payload capacity through hardware reinforcement can lead to greater complexity, increased weight, and higher energy consumption. A more efficient approach is to separate the feeder from the robot, using a hose or flexible conduit for material delivery. This reduces the robot's structural load and simplifies payload management.

- C3(TC5 ↔ TC1, TC2 - Locomotion Method and Mobility

  The choice of the locomotion method significantly impacts the robot's mobility and suitability for various work environments. For construction sites, six-wheeled or tracked systems provide enhanced stability and manoeuvrability. However, these configurations can increase the robot's size and weight, making it less suitable for confined spaces or sites with restricted access. In contrast, a compact wheel-based or legged system may offer better flexibility but could compromise stability on uneven surfaces. Therefore, it is critical to carefully balance the trade-offs between mobility, stability, and size to ensure the robot is practical for real-world applications.

- C4(TC6 ↔ TC4) - Multi-Manipulator Spray Control

  Utilizing multiple manipulators for spray control can offer several advantages, such as reducing the spray load per manipulator and improving the uniformity of the applied coating. This is especially beneficial for achieving consistent thickness, as smaller quantities of material can be applied more accurately. However, this approach significantly increases the overall payload, requiring the supporting platform to have sufficient load capacity. Additionally, the increased number of manipulators demands higher power supply capacity, more complex control systems, and reinforced structural components. A balanced approach is necessary, where the benefits of multiple manipulators are weighed against the added complexity and hardware requirements.

These contradictions, summarized in Table 4, provide critical insights into the trade-offs that must be managed in the design of fireproofing spray robots.

Table 4. Technical contradictions

Contradiction	Pair	Description
C1	TC6 ↔ TC7, TC9	Sensors must maintain clear visibility but are at risk of contamination.
C2	TC4 ↔ TC14	Maintaining a stable payload is challenging due to material weight change.
C3	TC5 ↔ TC1, TC2	Increasing stability by size reduces mobility.
C4	TC6 ↔ TC4	Multiple manipulators improve control but increase payload.

4.4. Design Alternatives to Mitigate Technical Trade-Offs

The correlation analysis in Section 4.3 identified several critical trade-offs among the technical characteristics (TCs). To address these conflicts, three design alternatives are proposed, each providing practical strategies for overcoming technical limitations in the conceptual design of fireproofing spray robots.

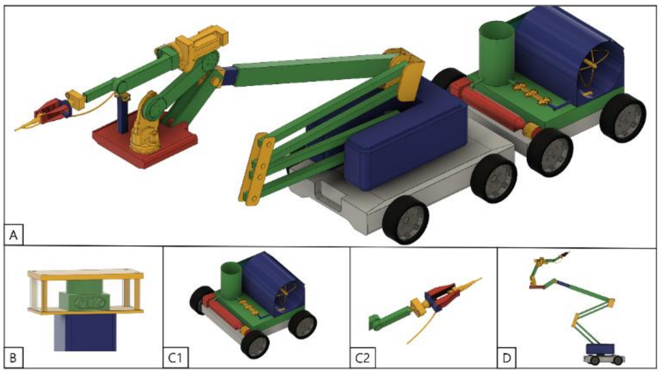

Figure 3. Design Alternatives (A: robot overall, B: Sensor module, C1: Follower robot, C2: gripper end effector, D: articulating lift example)

4.4.1. Design Alternative 1: Sensor contamination prevention

If fireproofing material splashes onto the sensor, as described in C1, it can cause sensor malfunctions. Therefore, a protective barrier is required to prevent foreign substances from adhering to the sensor. In various industrial settings, cleaning methods are used to remove contaminants from sensors. For instance, a Korean automobile manufacturer has developed a cleaning system for its vehicle sensors, such as LiDAR and cameras, which inevitably become contaminated while driving. This system employs a nozzle that sprays liquid onto the sensor, combined with a wiper blade, and uses a rotating cover glass to clean the surface. Although this method is complex, it effectively removes foreign substances.

However, the material used in fireproofing spray robots is different from ordinary contaminants. The material typically has larger particles and higher viscosity. If a wiper blade is used to remove it, streaks are likely to remain. While spraying cleaning liquid can help remove contaminants, it adds complexity, such as the need for refilling the liquid and maintaining the system.

As a more efficient alternative, a film-based protection method is proposed. Instead of using a washer fluid and wiper blade, this design uses a protective film that is replaced automatically. When the film becomes contaminated, a new film is deployed, similar to how a film camera advances its roll.

As shown in Figure 3-B, the design includes a cylindrical module surrounding the sensor, containing a roll of protective film. When the cylinder rotates, the contaminated film is collected onto a separate spool, while a fresh film is unrolled to cover the sensor. Although the film must be manually replaced when fully consumed, this is similar to maintaining a washer fluid and wiper system.

4.4.2. Design Alternative 2: Modular follower mobile robot and gripper end effector

The weight of the fireproofing spray material feeder dynamically changes during operation. Therefore, if the feeder is mounted on the robot, it is essential to account for the variable weight. Instead, considering the multi-purpose applicability of the robot, the system can be divided into a leader robot (working robot) and a follower robot (supply robot). The supply robot, equipped with a feeder, transports the material through a hose using a pump, while the working robot performs the spraying task.

As in Figure 3-C1 this modular design allows for the supply robot to be replaced independently in case of feeder failure, ensuring operational continuity even in unexpected situations. Moreover, the modular design of the follower robot can be extended beyond material supply to include other roles, such as transporting materials or equipment.

For this modular follower robot, it is recommended to equip the working robot's manipulator with a gripper-type end effector as shown Figure 3-C2. Fixing the end effector for a specific task limits the robot's multi-purpose functionality. Although manual replacement is possible, a gripper-type end effector allows for faster and more efficient tool switching between tasks, minimizing the need for manual intervention.

4.4.3. Design Alternative 3: 4-wheel drive and articulating lift

In construction sites, equipment is generally classified into two main types: tracked vehicles and 4-wheel drive vehicles. Tracked equipment is typically used for heavy-duty tasks and is itself heavy. These machines are designed to operate on uneven or unreinforced surfaces. However, the operating environment of the fireproofing spray robot is significantly different from such conditions. While the fireproofing spray robot will also operate in a construction site, the ground is generally rougher than ordinary surfaces, with variations in height. However, since the robot operates when the structural frame of the building is nearly complete, it is unlikely to encounter extremely rough terrain.

For this reason, a 4-wheel drive system is more suitable than a tracked system. The decision not to use a 6-wheel drive is based on space and efficiency considerations. Although 6-wheel systems provide better stability on uneven terrain, the internal environment of a building during fireproofing is relatively flat, making 4-wheel drive a more practical choice.

Additionally, to accommodate high-altitude tasks, an articulating lift system is proposed. Lift systems can be classified into two main types: vertical lifts and articulating (boom) lifts.

- Vertical Lift: This type operates like a forklift, providing vertical height adjustment for high-altitude work. However, it must be positioned precisely at the work location and is less effective for long, horizontally extended structures. Furthermore, it may require stabilizing mechanisms to prevent shaking during operation.

- Articulating Lift: This type operates like an excavator, extending and retracting to provide both vertical and horizontal reach. As shown in Figure 3-D, it is directly connected to the mobile base of the robot, eliminating the need for additional stabilizing mechanisms. This makes it more versatile for tasks involving long beams or extended surfaces.

5. Conclusion

This study applied a Quality Function Deployment (QFD) approach to develop a fireproofing spray robot, ensuring that customer requirements (CRs) were systematically identified and effectively translated into technical characteristics (TCs). Through QFD analysis, four critical design contradictions (C1–C4) were identified, each presenting unique challenges in the robot's performance. These contradictions were addressed through four practical design alternatives: a sensor contamination prevention film, a modular follower mobile robot and gripper end effector, and a 4-wheel drive with an articulating lift. These solutions significantly enhanced the robot's adaptability, performance, and operational efficiency.

This research highlights the importance of user-centered design in robotic development, providing a clear framework for resolving design conflicts and optimizing technical solutions. However, the proposed designs were not tested in real-world conditions, and the control strategies remained at a basic level. Future research should focus on real-world testing, advanced control systems, and multi-material spraying capabilities to further enhance the robot's performance and versatility.

Acknowledgements

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