**Application of Quality Function Deployment for Design and Development of Artificial Muscle Fabrication Device**

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Abstract— The field of artificial muscles has garnered significant attention due to their suitability for biomedical and robotic applications. Particularly, twisted, and coiled nylon fiber actuators, a type of artificial muscle, exhibit significant potential. However, the current manufacturing process for these actuators often lacks consistency and repeatability. Moreover, existing fabrication devices demonstrate a marked limitation, specifically, their capacity to generate only a single kind of artificial muscle. This study proposes the application of the Quality Function Deployment framework to design and develop a reliable machine for fabricating twisted and coiled artificial muscle. An array of customer requirements was obtained from literature and survey, and these were prioritized and translated into product specifications via the QFD tool. The proposed design addresses several key requirements, including the capability to fabricate distinct types of artificial muscles, automated operation, and improved product uniformity. The implementation of QFD offers a structured and customer-focused approach that helps in concept design generation by considering the priority of customers and the importance of technical specifications. Future studies are recommended to validate the proposed design with prototyping and testing.

Keywords— Quality Function Deployment, Artificial muscle, Customer requirement, Nylon fiber, Fabrication device.

1. INTRODUCTION
2. Background

The study of artificial muscles has shown significant advances because of their suitability for biomedical and robotic applications in terms of improved mechanical properties (power density, specific power, strain), softness, acceptable efficiency, and silent operation. Artificial muscle is a term used to refer to actuators or materials that behave like biological muscles and are capable of producing and controlling motion within a component or system via contraction, expansion, or rotation in response to an external stimulus such as an electric current, chemical, pressure, temperature, or light [1, 2]. There are numerous types of artificial muscles that can be used for industrial and biomedical applications. In most cases, the types of material used to produce artificial muscles are polymers. Different active polymers with varying programmable properties are evaluated in response to various actuation mechanisms. Twisted and coiled nylon fiber (TCNF) actuators are among those artificial muscles that show considerable strain when subjected to heating. This characteristic of high strain capability renders TCNF actuators for utilization in a variety of actuating applications. TCNF artificial muscles are made from silver-coated nylon material such as can be found in fishing lines and sewing threads [3]. The addition of an electrically conductive heating element using coating or wire winding to the polymer fiber enables electrothermal actuation by Joule heating [3-5]. TCNF actuators have a wide range of applications, including robotics, prosthetics, soft robotics, medical devices, aerospace, automotive engineering, and the textile sector [3, 6]. There are two types of TCNF coils 1) Homochiral and 2) Heterochiral: the homochiral coil is made when coiling and twisting have the same chirality, and it contracts when exposed to heat. In contrast, heterochiral coils are produced when coiling and twisting have opposite chirality, and they expand or elongate when subjected to heat [4].

TCNF artificial actuators can be easily fabricated by first twisting nylon fiber and then coiling the twisted fiber into a helical spring-like structure. TCNF actuators are conventionally constructed using a simple mechanism in which the precursor nylon fiber is twisted axially by using a controllable motor driver until it begins to coil onto itself while the other end is attached to a weight [3, 7, 8]. This method, however, would not produce consistent results. Moreover, the fiber will break or become tangled if the hanging weights and rotation speed are not appropriately selected. Therefore, to obtain reliable results and maintain repeatability, designing and constructing a fabrication machine capable of consistently fabricating twisted and coiled artificial muscles is necessary.

From prior research, it has been observed that Semochkin [9] was instrumental in constructing the first automated fabrication device. This device possesses the capacity to manufacture artificial muscles by incorporating a heater wire for joule heating actuation. Despite this noble achievement, the system still requires manual human intervention during the fabrication process. S. A. Horton and P. Dumond [10] developed a device having two different components to produce the artificial muscle: the first component prepares a consistent filament section while the second device twists and coils the filament thus rendering the fabrication process a sequential two-phase procedure. An apparent limitation of the two devices [9, 10] is their exclusive ability to manufacture homochiral actuators, with an absence of the capability in producing heterochiral ones.

In this study, we proposed to apply the Quality Function Deployment (QFD) framework to design a TCNF artificial muscle fabrication machine. QFD is a structured approach to defining customer needs or requirements and translating them into technical requirements for each stage of product design and development [11]. The purpose of this study was to implement the QFD tool in the design and construction of the fabrication device. This paper discusses developing a concept design for an artificial muscle fabrication machine using the QFD tool.

1. MEthods

This study is focused on employing the QFD framework for the design and construction of a fabrication device dedicated to the production of twisted and coiled artificial muscles utilizing nylon fibers. The resulting artificial muscles will be utilized in forthcoming research projects. The research work was conducted in the Mechanical and Materials Engineering department at Queen’s University, Canada. QFD is introduced in order to translate customer requirements into technical requirements or engineering specifications, subsequently into part characteristics, then finally into production requirements. The current study primarily focuses on the first phase of the QFD framework, as our aim is to develop the fabrication device for research and teaching purposes rather than targeting the commercial market. The first phase of QFD (product planning phase) also commonly called “the House of Quality” involves creating a house consisting of different sections as shown in Figure 1 [12] . It is a conceptual map that facilitates inter-functional planning and communication. The construction of the House of Quality for our design was executed by adhering to the subsequent procedural steps.

## Gathering Customer Requirements

The first step in building the house of Quality is to collect customer requirements (CRs) from different customers. CRs are articulated phrases used by customers to express their expectations regarding the product and its associated characteristics. CRs are usually referred as voice of the customer (VOC) which are captured in a variety of ways: direct discussion or interviews, surveys, focus groups, customer specifications, observation, warranty data, literatures etc. [11]. In this study, CRs are collected from two sources 1) from various existing literature and 2) through the implementation of a customer survey. The customers identified in this study are researchers, laboratory team members, and technical assistants. To facilitate the survey, seven copies of questionnaires were prepared and administered to the customers. The questions were categorized into 4 groups: 1) Production capability 2) Maintenance and operation 3) Safety and cost 4) Performance and durability. The collected CRs were subsequently categorized into distinct bundles of requirements, classified as primary and secondary representing the full range of customer concerns.

## Weighting Customer Requirements

The second step is to analyze the importance of each requirement by weighing on a scale of 1-5 which is described in section 2 of the HoQ in Figure 1. Weightings are determined from team members’ direct experience with customers and from surveys [13].

## Technical Requirements

Following the process of identifying and establishing priority for customer needs, the next step involves the development of Technical Requirements (TRs) to meet the identified needs. TRs are engineering specifications that describe the product in quantifiable terms and have a direct impact on customer requirements [13]. TRs are determined from engineering knowledge, existing literature and competitors’ products.

## Prioritize Technical Requirements

Once technical requirements are identified, the next step is to determine the importance of each TR. The technical importance rating will be used to determine the priorities for each design requirement. The absolute technical importance of each TR is calculated as follows [14]:

Where *TRj* is the absolute technical importance of technical requirement, *CMij* is a quantified relationship between CR and TR, *CRi* is the percentage weight of each customer requirement and *n* is the number of TRs.

## Relationship Matrix

The relationship between CR and TR is determined by the research team members and it can either be weak, moderate, or strong which have a numeric value of 1, 3, or 9 [14].

## Comparative Assessment

In this section, a competitive analysis was conducted comparing existing products. Ideally, these evaluations are based on scientific surveys of customers. However, given that the fabrication device under investigation is currently unavailable commercially, the competitive analysis was conducted solely with consideration of research-based designs.

## Operational Target

At this stage in the process, the QFD team begins to establish target values for each TR.

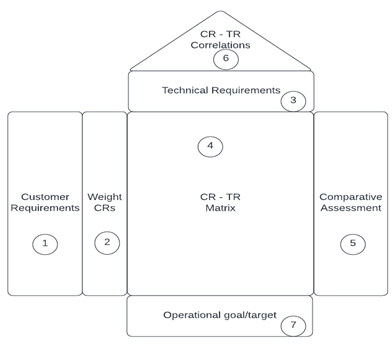


Figure 1: House of Quality Template

1. RESULTs
2. *Customer Requirements*

Customer requirements are obtained from surveys and literature. There are 15 CRs listed with their corresponding weights of importance on a scale of 1 – 5 as shown in table 3.1 below. The 15 CRs, which are referred to as Secondary CRs, are bundled into 8 primary CRs. Among all the CRS “Produce homochiral artificial muscles”, “Produce TCNF muscles made of metal coated fiber”, “Produce heterochiral artificial muscles”, and “Uniformity of products” were the most important items having the weight of 5. On the contrary, “Easy to handle and transport”, “Ease of Cleaning and lubrication”, and “Easy of assembly and disassembly for maintenance” are identified as the least important requirements.

Table I: List of Customer Requirements

|  |  |  |  |
| --- | --- | --- | --- |
| **Primary CRs** | **Secondary CRs** | **Weight** | **Percentage** |
| Production Capability (Produce different types of AMs) | Produce homochiral artificial muscles | 5 | 11.11 |
| Produce heterochiral artificial muscles | 5 | 11.11 |
| Produce TCNF muscles made of metal-coated fiber | 5 | 11.11 |
| Produce TCNF muscles made of wrapped wire | 4 | 8.88 |
| Operation | Simple to operate and control | 3 | 6.67 |
| No human intervention | 3 | 6.67 |
| Repeatability | Uniformity of products | 5 | 11.11 |
| Maintenance | Easy of assembly and disassembly for maintenance | 2 | 2.22 |
| Ease of Cleaning and lubrication | 2 | 2.22 |
| Cost Effective | Material cost | 3 | 6.67 |
| Safety | Contact with moving part | 2 | 4.44 |
| Easy to handle and transport | 1 | 2.22 |
| Durability | Long life | 4 | 8.88 |
| Performance | Productivity | 3 | 6.67 |
|  | Time |  |  |

1. *Technical requirements*

TRs are engineering design requirements developed by the design team in order to fulfill the customers’ needs. After identifying the technical requirements, they are prioritized based on their impact on meeting customer needs and their practicability as shown in Table II**.** It is observed thattwisting motor capacity, coiling motor capacity, automation and control system are the most prioritized design requirements. On the other hand, weight, overall size, structure of support material, and vibration are the least important technical requirements in the design process.

Table II: Technical requirements and their importance

|  |  |  |  |
| --- | --- | --- | --- |
| **No** | **Technical Requirements** | **Technical Importance** | |
| **Absolute** | **Relative** |
| 1 | Twisting Motor Capacity | 405 | 17.75 |
| 2 | Coiling Motor Capacity | 336 | 14.73 |
| 3 | Overall Size (Dimension) | 34.09 | 1.49 |
| 4 | Feature to use wound wire | 81.8 | 3.59 |
| 5 | Weight | 20.454 | 0.90 |
| 6 | Frame/Structure material | 129.53 | 5.68 |
| 7 | Automated | 252.25 | 11.06 |
| 8 | Means of fastening | 65.9 | 2.89 |
| 9 | Mechanical end-stop switch | 177.22 | 7.77 |
| 10 | Number of moving parts | 102.26 | 4.48 |
| 11 | Structure support material | 52.27 | 2.29 |
| 12 | Control system | 249.97 | 10.96 |
| 13 | Structural integrity (Strength) | 74.99 | 3.29 |
| 14 | Vibration | 68.18 | 2.99 |
| 15 | Overall speed of machine | 88.63 | 3.88 |
| 16 | Manufacturing precision | 143.18 | 6.28 |

1. *The House of Quality*

The construction of the HoQ, as shown in Table 3, consisted of five primary sections. These sections comprise: (1) the CR; (2) the TR; (3) the Relationship between CR and TR; (4) Competitive Analysis; and (5) Target Values. Based on the outcomes derived from the House of Quality (HoQ) analysis, we proceeded to formulate general device specifications and concept design. Based on the results of QFD, a simplified 3D model of the proposed fabrication device was developed as shown in Figure 2.

A diagram of a machine

Description automatically generated

Figure 2: Simplified 3D model of Fabrication Device

1. CONCLUSIONS

The findings of our study demonstrated the benefits of utilizing the QFD framework in understanding and meeting the different needs and wants of the customers. An interesting finding was the customers’ preference for the device to fabricate distinct types of artificial muscles, including both homochiral and heterochiral TCNF muscles. As a result, these requirements were integrated into the design. Moreover, the application of QFD, notably during the first phase, enabled a successful derivation of technical specifications, each accompanied by an appropriately calculated weight. Such an achievement underscores the effectiveness of QFD in fostering the alignment of TRs with customer needs. Utilizing the data obtained from the QFD analysis, a 3D model of the fabrication device was generated, taking into consideration of the specified CRs.

Conflict of Interest

The authors declare no conflict of interest.

REFERENCES

[1] M. Shahinpoor, K. J. Kim, and M. Mojarrad, *Artificial muscles: applications of advanced polymeric nanocomposites*. CRC press, 2007.

[2] S. M. Mirvakili and I. W. Hunter, "Artificial muscles: Mechanisms, applications, and challenges," *Advanced Materials,* vol. 30, no. 6, p. 1704407, 2018.

[3] C. S. Haines *et al.*, "Artificial muscles from fishing line and sewing thread," *science,* vol. 343, no. 6173, pp. 868-872, 2014.

[4] A. Cherubini, G. Moretti, R. Vertechy, and M. Fontana, "Experimental characterization of thermally-activated artificial muscles based on coiled nylon fishing lines," *Aip Advances,* vol. 5, no. 6, p. 067158, 2015.

[5] M. C. Yip and G. Niemeyer, "On the control and properties of supercoiled polymer artificial muscles," *IEEE Transactions on Robotics,* vol. 33, no. 3, pp. 689-699, 2017.

[6] S. Y. Yang *et al.*, "Soft fabric actuator for robotic applications," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2018: IEEE, pp. 5451-5456.

[7] K. H. Cho *et al.*, "Fabrication and modeling of temperature-controllable artificial muscle actuator," in *2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, 2016: IEEE, pp. 94-98.

[8] L. Saharan and Y. Tadesse, "Fabrication parameters and performance relationship of twisted and coiled polymer muscles," in *ASME International Mechanical Engineering Congress and Exposition*, 2016, vol. 50688: American Society of Mechanical Engineers, p. V014T11A028.

[9] A. N. Semochkin, "A device for producing artificial muscles from nylon fishing line with a heater wire," in *2016 IEEE International Symposium on Assembly and Manufacturing (ISAM)*, 2016: IEEE, pp. 26-30.

[10] S. A. Horton and P. Dumond, "Consistent manufacturing device for coiled polymer actuators," *IEEE/ASME Transactions on Mechatronics,* vol. 24, no. 5, pp. 2130-2138, 2019.

[11] D. R. Kiran, "Chapter 30 - Quality Function Deployment," in *Total Quality Management*, D. R. Kiran Ed.: Butterworth-Heinemann, 2017, pp. 425-437.

[12] A. S. Institute, "QFD–Kundorienterad produktutveckling hårdvara & process," ed: American Supplier Institute Inc. Dearborn, 1992.

[13] J. R. Hauser and D. Clausing, "The house of quality," 1988.

[14] G. S. Wasserman, "On how to prioritize design requirements during the QFD planning process," *IIE transactions,* vol. 25, no. 3, pp. 59-65, 1993.

Table III: House of Quality

