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Phygital Design of an Innovative and Portable Autosampler Using Shape Memory Alloy-based Mini-actuator for River Quality Assessment

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The evaluation of river water quality is of paramount importance in the maintenance of the well-being and durability of our water reservoirs. Real-time sensors can be used to analyze river water properties, but being able to automatically extract water from a natural setting for controlled laboratory analysis can expand research opportunities in quality assurance and test types. In this paper, we outline the conceptual design of a portable submersible autosampler. Quality function deployment prioritizes customer needs by utilizing both physical and digital (phygital) means, including interviews conducted both physically and virtually, and transforming them into precise design attributes represented in digits within a house of quality. The proposed device incorporates a nickel and titanium (NITINOL)-based shape memory alloy (SMA) spring architecture to draw water samples from rivers effectively via an active syringe. SMA-based actuation is proposed as a disruptive technology owing to its benefits, such as its lightweight, high energy density, and corrosion resistance. The autosampler can collect up to 10 samples at user-controlled intervals. Open-source Arduino hardware and software are incorporated with the actuator, allowing customization for deployment needs. In this autosampler, water samples are collected in a syringe, and the volume of water is determined by the SMA spring's actuation time.

1. Introduction

Water depletion in India is primarily caused by rising populations, agricultural expansion, climate change, water contamination, and diminished freshwater reserves. Contemporary anthropogenic activities have resulted in the introduction of an array of unparalleled chemical substances into marine as well as freshwater systems.(1) These substances include toxic chemicals, herbicides, petroleum-based goods, commercial waste, and emerging pollutants such as chemicals, personal care goods, legal and illegal drugs, plastic items, and nutrients such as

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nitrogen and phosphorus from fertilizer, waste from agriculture, and effluent.(2) The depletion and contamination of groundwater endanger human health, disrupt agricultural production, disturb the equilibrium of aquatic and terrestrial ecosystems, and contribute to climate change.(3)

The chemical composition and ambient conditions of the aquatic environment undergo significant fluctuations, both spatially and temporally. Even minor changes in variables such as rainfall, water depth, wind strength, wave movement, and animal behavior can lead to rapid environmental changes.(4) The collection of water samples from deep estuaries, waterways, or streams, especially in areas with limited accessibility, may present challenges. Traditional sampling methods that utilize upward tubes of either plastic or metal, such as Nansen and Niskin bottles, are not suitable for estuaries during low tide owing to low water levels that can be below a meter deep.(5)

An organized methodology that accounts for user inclinations and requisites is imperative.(6) Quality function deployment (QFD) highlights a product's strengths and limitations, enabling novel products and services to be created.(7) Historically, QFD has demonstrated efficacy in facilitating the design and development of technical requirements for novel products, as well as enhancing pre-existing products across various industries and sectors, including but not limited to robotics, aerospace, automotive production, applications, interaction, computer technology, and transportation.(8) The QFD method was utilized by Pasawang *et al.* to devise a preliminary concept of an autonomous underwater robot intended for military operations.(9) Shukla and Bhattacharya used QFD to conceptualize the drafting of an aquatic autonomous observatory for river water quality monitoring.(10) The conventional method for obtaining water quality data typically involves manual sampling using bottles or other vessels. Obtaining a solitary water sample is a straightforward task that facilitates several meticulous laboratory assessments. Collecting water samples in bottles, that is, bottle sampling, is a cost-effective and simple method. However, it only offers data from when the sample was taken. Bottle sampling requires significant labor and resources, which may vary depending on the locality. Utilizing a limited sample size for evaluating chemical contaminants can result in imprecise findings. Bottle sampling is limited to periods when there are favorable working conditions for humans, such as good weather, calm river or sea conditions, and easy access to the sampling site.(5) As a result, it may not capture important short-term, high-intensity episodic events. In contrast, manual depth sampling using Niskin or Van Dorn samplers requires ease of access, as well as secure working environments. The limitation of being unable to collect samples simultaneously from multiple locations is a challenge for bottle sampling when attempting to capture brief, sporadic occurrences across various study sites.

In 2007, Bird *et al.* developed a specialized seawater sampler designed for autonomous underwater vehicles (AUVs), utilizing a syringe-based technique.(11) The device collects a total of 2 L of seawater in 10 samples at depths of up to 300 m. Although the sampler is compatible with AUVs, its substantial dimensions pose challenges for manual sample collection in the ocean. The large size of this sampler poses a difficulty, particularly when doing hand sampling operations. One way to solve the limitations of bottle sampling in freshwater research is using Instrumentation Specialties Company (ISCO)-style samplers.(12) These sampling systems are designed to collect water using an electric pump. The water is collected into a sequential rosette, which is made up of a specific number of sample bottles. A programmable time frame controls the collection process. Although these samplers have the potential to gather a limited number of separate samples independently, they are notable for their large dimensions (69 cm diameter, 51 cm height), hefty weight (15 kg), and high price (varying from $2.5k to $5k), even for the most straightforward and smallest models. Carvalho developed a portable and open-source autosampler designed to collect samples from shallow seas.(13) These inexpensive ($567) open-source alternatives are, however, not waterproof, limiting their usage to investigations that need sampling on land near water bodies. Therefore, placing them in secure enclosures is frequently necessary to enhance their durability against adverse weather conditions and unauthorized access. Mucciarone *et al.* have recently created an autonomous submersible multiport water sampler designed for use in river environments.(14) This commercial submersible multiport system is expensive ($35k to $45k). Although high-capacity systems are sometimes expensive, most freshwater or coastal research is conducted at depths of less than 30 m, making them redundant. Recently, sampling systems developed by researchers and made available as open source have provided an affordable alternative compared with commercial options.(11–13) These systems are particularly well suited for deep deployments. However, they often require several enclosures, exposed pump elements, and external containers for water sample collection. Although this increases sample size and reduces cost, it also enlarges the system's physical space, adds complexity, makes it more susceptible to damage and tampering, and creates more potential areas where it could fail. Therefore, these systems may be insufficient for collecting samples in high-energy environments, such as fast-flowing rivers, areas below the low tide mark with strong waves or locations with abundant debris, like rivers during storm surges or wastewater canals.(12,13) Enochs *et al.* presented a comprehensive description of the creation, usage, and efficacy of a low-cost (<$220) subsurface automated sampler (SAS) intended explicitly for gathering water samples to analyze carbonate chemistry below the water's surface.(15) The SAS can collect two samples simultaneously using bags with a maximum volume of 900 ml. Mucciarone et al.'s sampler and SAS can collect water samples: at a specific predetermined time and day or once per day. SAS is well suited for situations requiring larger sample volumes or a greater number of different samples.

Among these sampler initiatives, our sampler is the most compatible and capable when compared with the programmable autonomous water sampler (PAWS) intended explicitly for monitoring water quality over time in aquatic environments.(16) Our sampler uses a syringe plunger-like slider mechanism programmed to collect water using a shape memory alloy (SMA) spring at a continuous rate to accomplish time-triggered water sampling. It can be deployed anywhere in the river up to a depth of 10 m, and the desired time of sample collection must be set before deployment. The collected water samples can be retrieved when the sampler is recovered. It has a one-way valve mechanism so that water will not remain in contact with the river after sample collection. Our completely autonomated sampler can collect multiple samples over time, which can be controlled by users' requirement of water sample analysis. Moreover, it has simple 3D-printed parts, it can collect at least 10 samples in a time-triggered mechanism, and it is inexpensive ($120 per unit) compared with PAWS ($300 per unit), which can collect only one water sample over a few minutes or longer. If we want to collect samples over multiple days, we need to deploy multiple units of PAWS; however, with our autosampler, we can increase the capacity of sampling units as per user requirements and deploy it for a longer period of up to weeks or months.

In this study, we outline the phygital design of an automatic water sampler, which has been developed with the primary objective of collecting water samples from shallow aquatic systems such as lakes, rivers, caves, and estuaries. The device employs a mini-actuator based on SMA technology to facilitate river quality assessment. SMA actuators exhibit superior force output in a compact form factor compared with conventional motor-based actuators.[17] The current design exhibits various advantages compared with its predecessors, such as compact dimensions, durability, and simplified implementation and management. The compact dimensions of the sampler render it lightweight, facilitating its transportation and deployment, and straightforward to assemble. The sampler is designed to be deployed in situ, enabling access to sampling opportunities otherwise inaccessible to land-based samplers. Moreover, we envision seamlessly integrating this autosampler into our existing buoy system, which is equipped with self-harvesting energy capabilities and ensures sustained operation of the monitoring system.[18]

2. Materials and Methods

QFD is a methodical design approach that holds significant importance in the advancement of novel products and the enhancement of pre-existing ones, guaranteeing their alignment with the specific demands of customers or users. QFD enables the conversion of customer requirements into technical specifications by establishing a connection between user needs and engineering design parameters. A wide range of resources, including scholarly papers and textbooks, provide comprehensive information and in-depth analysis of the QFD process, as shown in Fig. 1(a). In the following section, we provide a concise overview of the QFD process using a house of quality (HOQ), which serves as a visual representation of customer needs and engineering characteristics. It provides a structured framework for translating customer needs into specific design features, fostering alignment between user expectations and product attributes integrated in the design of an autosampler for quality assessment purposes.

2.1 Identification and prioritization of customer requirements

This is the primary stage in the process of discerning customer requirements that pertain to both direct and indirect aspects of the river quality assessment system. In this step, we conducted surveys, interviews, and discussions with the people associated with stakeholders (environmental agencies, researchers, etc.) to identify customer requirements or opinions regarding the autosampler. In essence, a sample size of 30–40 individuals for interviews is generally considered sufficient to capture approximately 95% of user requirements.

The relative importance (RI) method is utilized to prioritize customer needs by assigning relative weights or scores to each requirement, considering its perceived significance to the customers. This methodology enables a methodical assessment of the relative significance of individual customer requirements in comparison with one another (1 = least important, 2 = not very important, 3 = quite significant, 4 = highly significant, and 5 = extremely important).

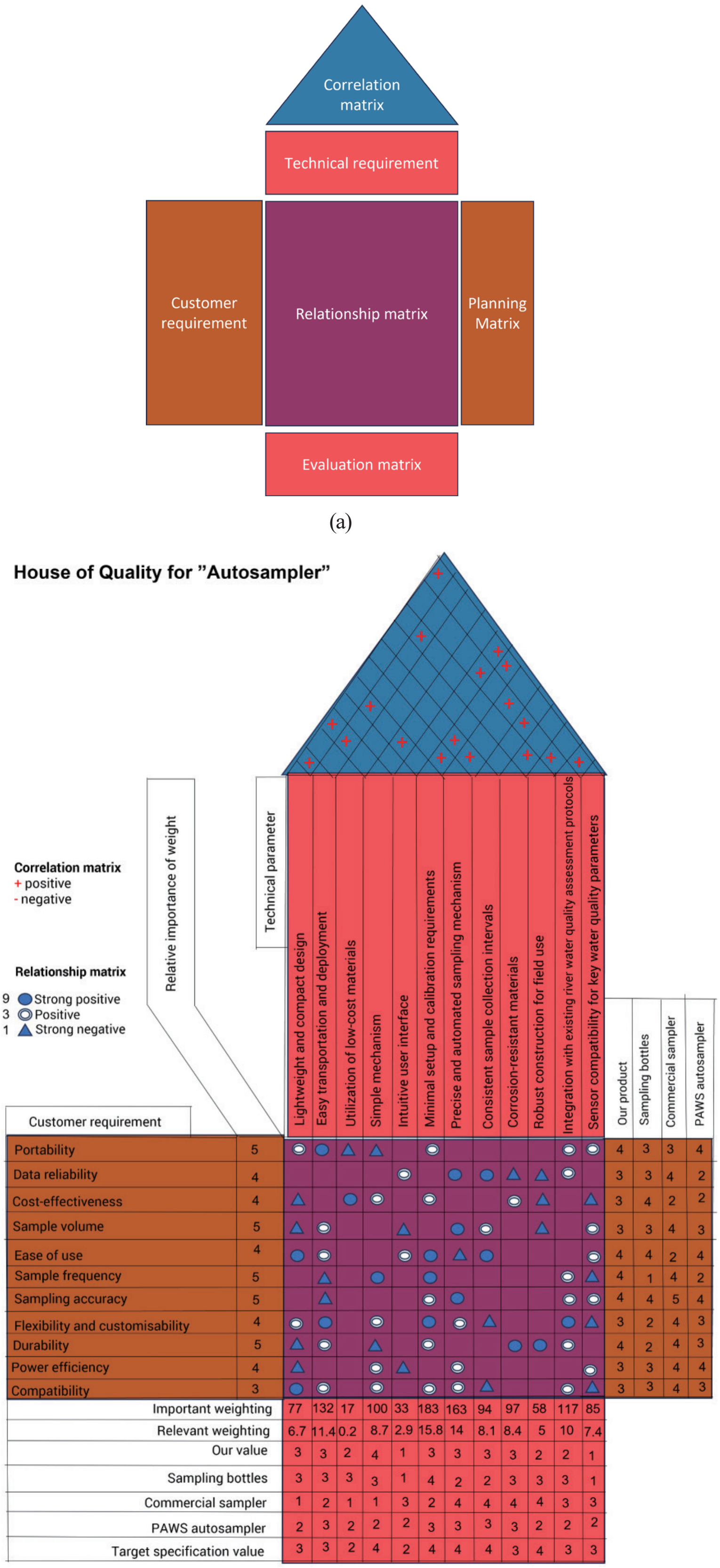


Fig. 1. (Color online) (a) Basic architecture of QFD method. (b) QFD analysis using HOQ.

$$RI = \sum_{j=1}^{N} \frac{W_j U_{rj}}{N} \quad (1)$$

Here, $r = 1, 2, 3, \ldots, R$, N = number of customers, U_{rj} = importance customer rating, W_j = weight of importance of customer decision, and $U_{r\cdot}$ = average importance rating relative to $X_{r\cdot}$ customer requirements.

2.2 Determination of design characteristics and establishment of relationships with customer requirements

Technical requirements play an essential part in bridging the gap between the customer requirements and the engineering characteristics that indicate the fulfilment of the design process. The process of developing the design that meets these requirements involves analyzing the functional needs described in the Sect. 2.1 while taking into consideration relevant professional expertise, application circumstances, industry standards, technological requirements, and other applicable aspects.

After identifying both the customer and technical requirements, it becomes imperative to determine their relationship by utilizing the input variables present in the main room of the HOQ. In the relationship matrix, a strong correlation is indicated by the value 9, whereas a moderate correlation is represented by 3, and a weak correlation is signified by 1.

2.3 Determination of planning matrix and setting of design target

During the product planning, it is important to perform a competitive technology review by comparing our product with similar products available on the market. On a scale of 1 to 5, this grid makes it easy to compare our goods with those of our competitors. The evaluation is supported by a comprehensive literature analysis, ensuring that we successfully address customer inquiries and satisfy their demands.

In the next step, we determined specific targets and specifications for each design characteristic on the basis of the relationship matrix and the desired level of customer satisfaction. We quantified the design targets in terms of importance weight to ensure a clear and measurable design goal.

$$IW = \sum \left(RI + CR \right) \quad (2)$$

Here, IW = Importance weighting, RI = Relative importance, and CR = Correlation rank.

2.4 Determination of correlation and design verification

In the final stage, we constructed a correlation matrix at the top of HOQ, which enhances our understanding of the interconnections among technical requirements. It is imperative to conduct a comprehensive investigation and analysis of the interrelationships among technical characteristics. The relationships among technical requirements can be classified into three categories: positive correlation (+), negative correlation (−), or irrelevance.

We developed validation methods and tests to verify that the design characteristics meet the specified targets and requirements. We conducted prototype testing, simulations, and other validation techniques to ensure the design's performance, functionality, and reliability.

3. Results

The results of each step of the method are described briefly below.

3.1 Identification and prioritization of customer requirements

In this step, we interviewed researchers, engineers, employees, and workers at the Center of Pollution Control Board Kanpur (CPCB), the irrigation department, Jal Vibhag, and people living near Ganga Ghat Kanpur. They were questioned about their nature of work, their duration of association with the Ganga River, things they would do to monitor water quality, the important water quality parameters, measurement methods, and so forth.

The relative importance ratings of the users' requirements listed in Table 1 were assigned subsequently, and the average importance ratings were computed using Eq. (1). The average importance ratings were subsequently incorporated into the HOQ. The importance ratings for the Y_r requirement, as presented in the table, were arranged in ascending order and graphically represented in Fig. 1(b).

Table 1
Relative importance rating.

Customer requirement	Customer rating					Average rating
	C_1	C_2	C_3	…	C_R	
Y_r	U_{r1}	U_{r2}	U_{r3}	…	U_{rR}	RI
Compatibility	2	3	2	…	4	3
Power efficiency	4	5	3	…	2	3.6
Data reliability	3	2	4	…	4	3.7
Ease of use	2	3	3	…	2	3.8
Cost-effectiveness	3	4	3	…	5	3.9
Flexibility and customizability	4	3	4	…	3	4
Durability	5	4	4	…	4	4.6
Sample volume	5	5	4	…	5	4.7
Sample frequency	5	4	4	…	4	4.75
Portability	4	4	5	…	4	4.8
Sampling accuracy	5	5	5	…	5	4.85

3.2 Determination of design characteristics and establishment of relationships with customer requirements

The technical characteristics were determined through a comprehensive analysis that considered multiple factors, including relevant literature and inputs from researchers at Indian Institute of Technology (IIT) Kanpur, engineers, and technical personnel in water monitoring laboratories affiliated with various pollution authorities in Kanpur. These factors considered pertinent expert knowledge, application conditions, industry standards, technological necessities, and other relevant facets.

The HOQ visually represents the linkage between user requirements and design characteristics through a matrix relationship as shown in Fig. 1(b). Every user requirement is correlated with multiple design parameters; conversely, each design parameter is connected to at least one user requirement. In addition, it is noteworthy that each user requirement exhibits a minimum of three connections with the design parameters and does not contain any vacant columns or rows.

3.3 Determination of planning matrix and setting of design target

In this matrix, a comprehensive evaluation was conducted to compare our product with other existing competitive offerings, such as the PAWS, commercial samplers, and recycled sampling bottles, using user-defined criteria. To evaluate these products, an extensive examination of pertinent literature was undertaken, resulting in the assignment of ratings on a 1 to 5 scale. The collected comparative data is subsequently graphically depicted in a figure to provide a visual representation, as shown in Fig. 2.

In the next stage, the weight of each design characteristic was determined by employing Eq. (2). The visual representation of the design weight and design target specification of our product, as compared with the design characteristics of other products, can be observed in the phygital model depicted in Fig. 2.

3.4 Determination of correlation and design verification

The present matrix was utilized to analyze the interrelationships among various design parameters. The design characteristics exhibit either a positive or no correlation, illustrating that there is a lack of negative correlation among the design characteristics as shown in Fig. 1(b).

QFD is used to develop the initial conceptual design of an SMA-based autosampler, as shown in Fig. 3(a). The SMA spring demonstrates the shape memory effect (SME) behavior, which is observed in the nickel–titanium (Ni–Ti) alloy family. In general, SMAs demonstrate two distinct phases that are dependent on temperature: the low-temperature phase and the high-temperature phase. Both phases exhibit distinct properties owing to the varying crystal structures present. The austenite phase, which is observed at temperatures above the transformation temperature, exhibits high strength and deformation resistance when subjected to load. The alloy exhibits comparable behavior to that of stainless steel, and therefore has high capacity to endure elevated

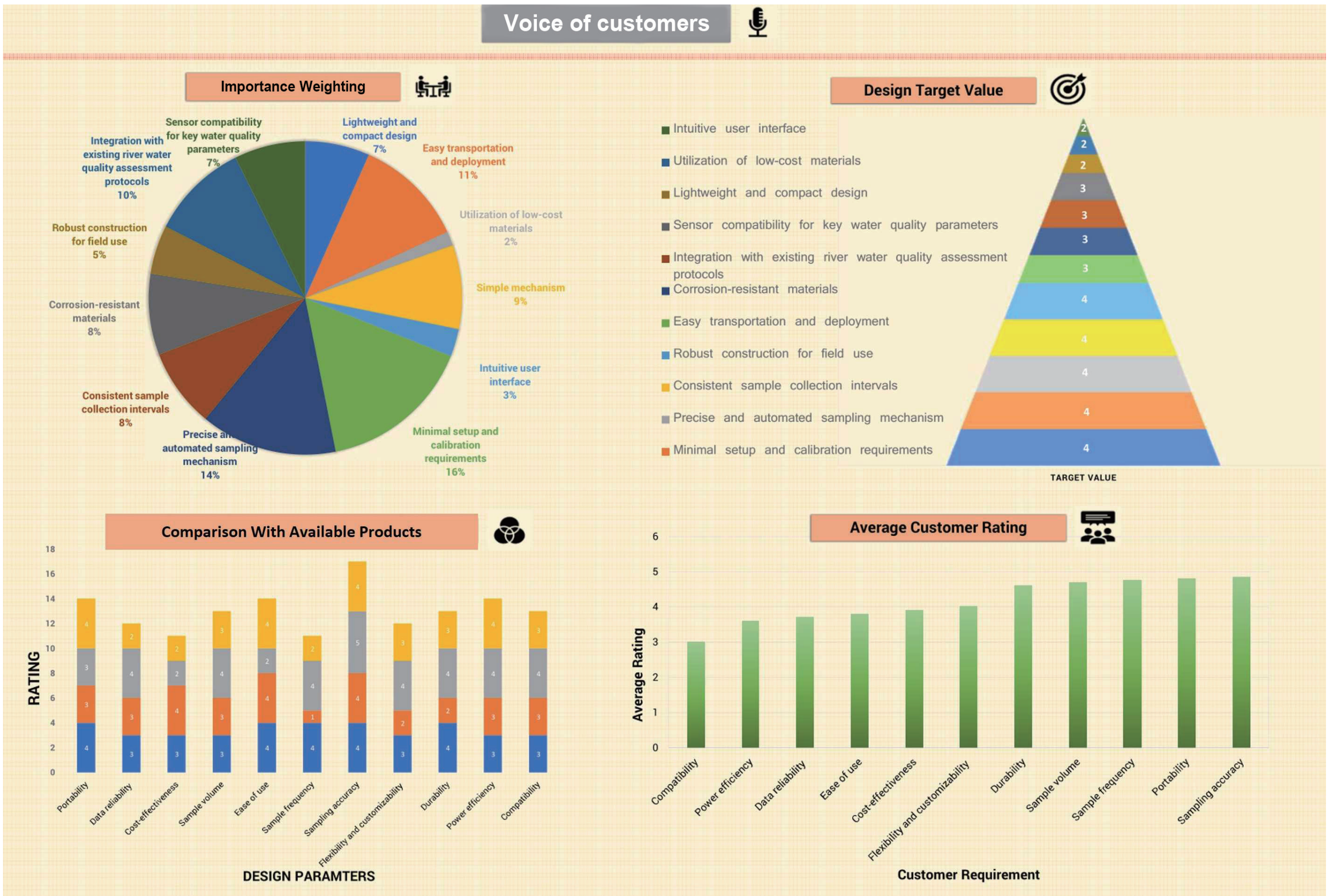
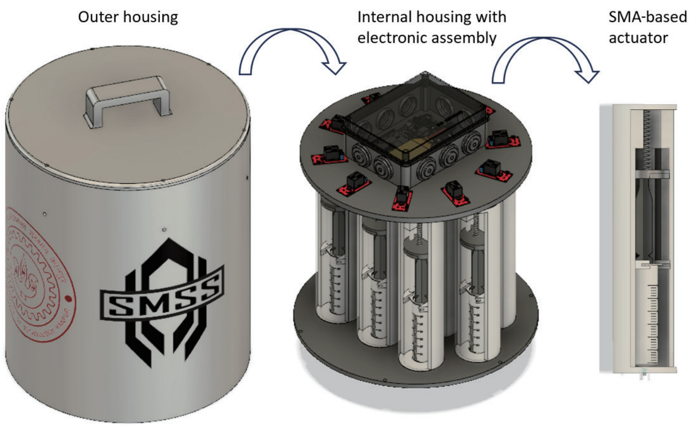
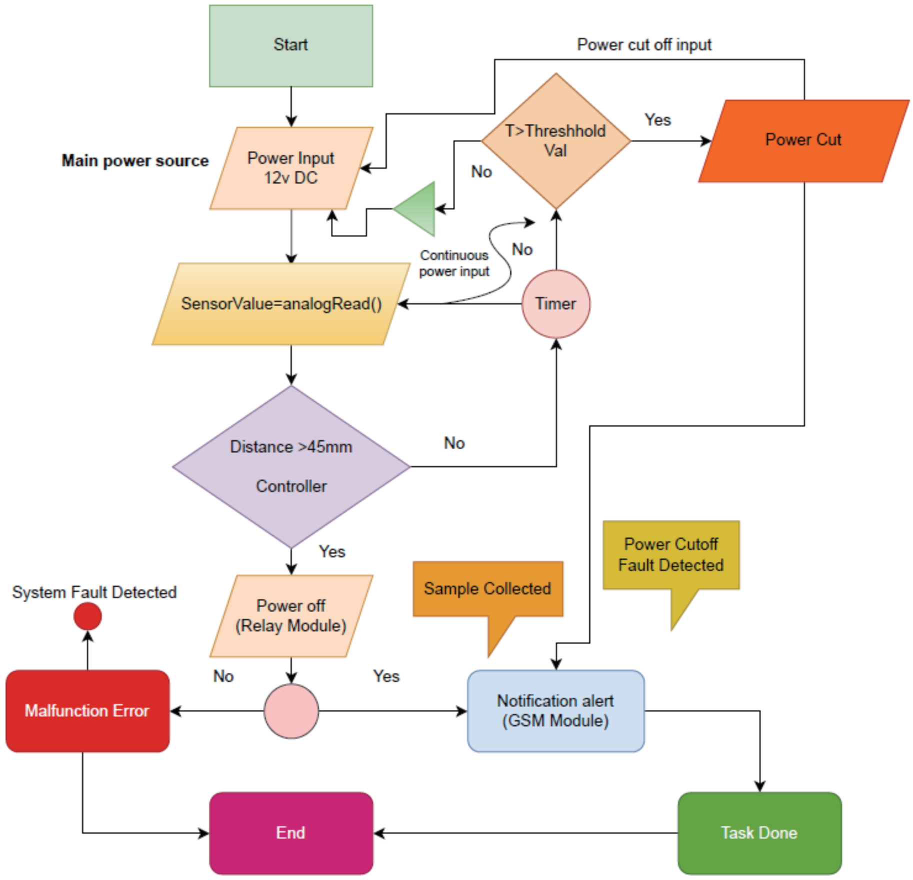


Fig. 2. (Color online) Phygital model based on the opinion of customers.



(a)

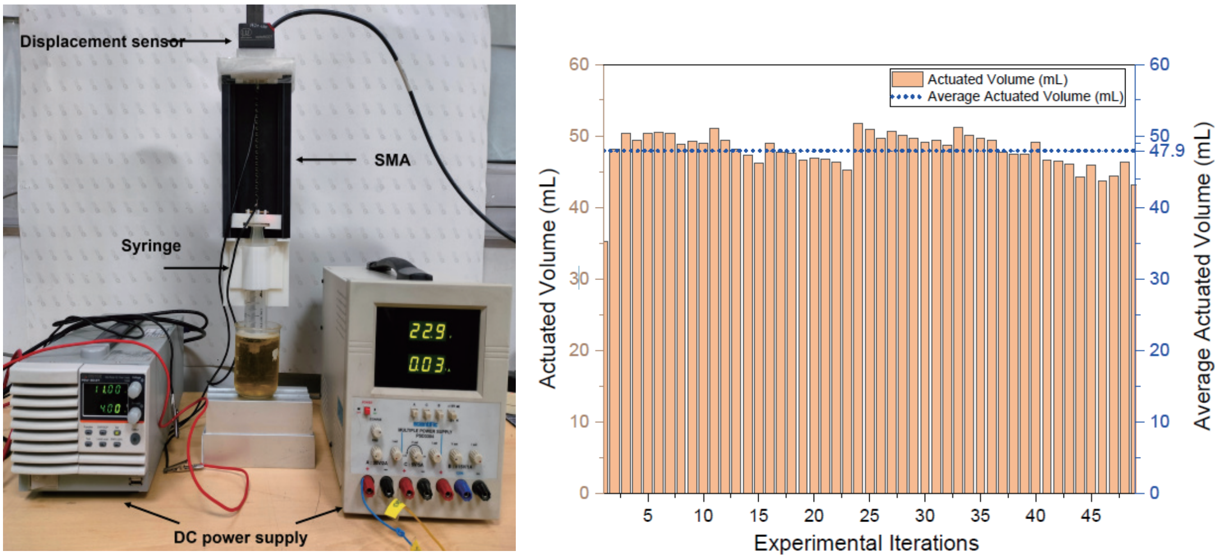
Fig. 3. (Color online) (a) Conceptual CAD design of autosampler. (b) Feedback flow chart for SMA actuation.



(b)

Fig. 3. (Color online) (Continued) (a) Conceptual CAD design of autosampler. (b) Feedback flow chart for SMA actuation.

levels of stress during actuation. By capitalizing on the inherent behavior of the Ni–Ti alloy, the SMA spring is affixed in a vertical orientation relative to the plunger, thereby creating an actuator mechanism for the purpose of water sample collection. In this conceptual design, an SMA spring-based submersible syringe system was designed and tested at the Smart Materials, Structures and Systems (SMSS) lab IIT Kanpur. The modular autosampler, shown in Fig. 3(a), can collect at least 10 samples at customizable intervals based on the user's needs. Arduino-based hardware and software integrated with the mini-actuator employ a time-triggered sampling methodology for collecting water samples. In addition, a unique feedback alert system, as illustrated in Fig. 3(b), was created. The purpose of this system is to transmit a notification to the user's mobile device if the syringe exceeds a volume of 45 ml upon activation. If the syringe fails to reach this threshold, the system will administer an additional current for a specified duration, represented as "T" seconds. We have developed the initial testing setup to test the actuation of a 50 ml surgical syringe via SMA, as shown in Fig. 4(a).



(a) (b)

Fig. 4. (Color online) (a) Testing setup for SMA actuation. (b) Syringe actuation volume using SMA.

4. Discussion

The HOQ encompasses all the designated design attributes and user demands, establishing their interconnections. Every user requirement is associated with a minimum of two design characteristics or more. The HOQ exhibits a lack of unfilled columns or rows, suggesting the absence of extraneous or duplicative parameters. The significant design parameters were identified from the HOQ by considering the design characteristics with the highest RI weight, as shown in Fig. 1(b).

The design mapping is depicted in Table 2. The findings emphasize the significance of the subsequent crucial design factors: the setup and calibration requirements are minimal. The proposed sampling mechanism demonstrates high levels of precision and automation, facilitating accurate data collection. Additionally, it offers the advantage of easy transportation and deployment, ensuring efficient implementation in various locations. Furthermore, the integration of this mechanism with established river water quality assessment protocols enhances its compatibility and usefulness within existing frameworks. The design parameters were employed to establish the anticipated design elements of an autosampler, as depicted in Fig. 3(a).

All the expected components have been identified on the basis of the literature review and expert's suggestions per user requirements and integrated into the conceptual CAD design, as shown in Fig. 3(a).

The experiment consisted of actuating a disposable surgical syringe with a capacity of 50 ml using an SMA spring. The spring was subjected to a resistance of 1 Ω and a current of 5 A, provided by a DC power source. A slider mechanism was used to connect the SMA and syringe plunger to collect water from the beakers. Meanwhile, a laser optical displacement sensor positioned on top of the testing setup, as shown in Fig. 4(a), measured the movement of the plunger. The power required for the system was 25 W. The syringe was tested under 50 different

Table 2
Design mapping.

Important design parameter	Expected feature
Minimal setup and calibration requirements	Feedback safety notification
Precise and automated sampling mechanism	Programmable hardware and software
Easy transportation and deployment	Modular electronic parts and components
Integration with existing river water quality assessment protocols	CPCB guidelines for sample collection
Simple mechanism	SMA-based piston cylinder actuation system

(a) (b)

Fig. 5. (Color online) (a) Single unit of autosampler. (b) Autosampler testing inside water tank.

iterations and its plunger mostly crossed the 50 ml mark. The average actuation volume by the syringe is 47.9 ml, as shown in Fig. 4(b), and the standard deviation for the system is 2.7854 ml during iterations. This level of precision is sufficient for accurately measuring parameters, such as pH, dissolved oxygen level, electrical conductivity, turbidity, and temperature, and indentifying microorganisms suc as *Escherichia coli*.

We have accomplished the development of a single autosampling device, depicted in Fig. 5(a). The sampling device incorporates modular design components that make it simple to assemble and remove the syringe after collecting the sample. The outside casing of this product is made from 3D-printed parts utilizing a polylactic acid (PLA) material, which provides both durability and simplicity in the assembly process. The electrical housing is strategically positioned on top of the sampler, guaranteeing efficient operation. To ensure hermetic functionality, an acrylic housing encloses the whole device. The unit's performance was validated through field testing conducted at a depth of 10 m in the oxidation pond at IIT Kanpur. The device underwent a rigorous 24-h operation cycle in a controlled environment, as shown in Fig. 5(b). It was submerged in a water-filled testing bath and programmed for a 24-h actuation period, and it successfully collected water samples. The price of one unit of this autosampler is around <$120, which makes it a more economical option than the PAWS, which costs $300. The unit weighs around 3 kg, with an extra 1 kg due to the acrylic enclosure. The size of the whole autosampler unit (capacity of 10 samplers) is estimated to be around 8.158 × 106 mm^3 with a steel body encloser, and the estimated total cost is approximately <$950, including electronics and sampling units.

5. Conclusions

The extensive range of research inquiries pertaining to the effect of water chemistry on aquatic environments is noteworthy. The aforementioned inquiries encompass a wide range of chemical constituents, temporal intervals, spatial dimensions, ecological niches, vertical distributions, hydrodynamic characteristics, and biological entities. Researchers specializing in marine and freshwater studies should possess a diverse array of tools to adequately address the wide range of issues within these fields. The provision of precise water chemistry data on spatial and temporal scales that are consistent with the dynamic fluctuations of aquatic conditions is of utmost importance. In this study, we utilized the QFD method to develop a conceptual design for an autosampler. Additionally, a phygital model was constructed on the basis of the inquiries of the users associated with the water monitoring and treatment authorities. The QFD was developed to provide a structured and methodical approach to identifying and capturing user requirements, as well as translating them into specific design characteristics. To align with user expectations and enhance satisfaction, the prototype development of an autosampler will incorporate design characteristics that carry significant weight. In this paper, we introduced an autonomous SMA spring-based water sampler. This device is characterized by its cost-effectiveness, robustness, and high adaptability, making it a valuable tool for various applications. This technology enables synchronized and extensive deployments, serving as either an independent sampling device or as a supplementary component to a broader research initiative.

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