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Original Article

QFD-based conceptual design of an autonomous underwater robot

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Abstract

Autonomous underwater robots in the past few years have been designed according to the individual concepts and experiences of the researchers. To design a robot, which meets all the requirements of potential users, is an advanced work. Hence, a systematic design method that could include users' preferences and requirements is needed. This paper presents the quality function deployment (QFD) technique to design an autonomous underwater robot focusing on the Thai Navy military mission. Important user requirements extracted from the QFD method are the ability to record videos, operating at depth up to 10 meters, the ability to operate remotely with cable and safety concerns related to water leakages. Less important user requirements include beauty, using renewable energy, operating remotely with radio and ability to work during night time. The important design parameters derived from the user requirements are a low cost-controller, an autonomous control algorithm, a compass sensor and vertical gyroscope, and a depth sensor. Of low-importance ranked design parameters include the module design, use clean energy, a low noise electric motor, remote surveillance design, a pressure hull, and a beautiful hull form design. The study results show the feasibility of using QFD techniques to systematically design the autonomous underwater robot to meet user requirements. Mapping between the design and expected parameters and a conceptual drafting design of an autonomous underwater robot are also presented.

Keywords: autonomous underwater robot, QFD, house of quality, Thai Navy, conceptual design, robot design

1. Introduction

Underwater robots, in the past few years, have become an important tool in underwater applications, especially in environmental and resource issues, including scientific and military tasks. Most of the underwater robots have to be operated under hazardous environments instead of human operations. Hence, the reliability and quality of an underwater robot have to be paid attention to. So far, there have been a number of the underwater robots being designed and developed to serve various applications (Blidberg *et al.*, 2001); often designed according individual concepts and experiences of the researchers (Yuh *et al.*, 2000; Altshuler *et al.*, 2002; Buesher *et al.*, 2002). This design method is convenience but may not actually meet the users or stakeholders requirements. Accordingly, a systematic design method that could include users' preferences and requirements is needed. Nowadays, there are a large number of such systematic design methods. One such method is the quality function deployment (QFD), which could relate the user requirements to the engineering product design and development. It translates the users' or customers' need into the technical design parameters at each stage of product design and production (Thomas *et al.*, 1996; Kondoh *et al.*, 2007).

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QFD originated in 1967 to develop new products in Japan (Mizuno *et al.*, 1978). Then in 1972, it was applied in the Mitsubishi shipyard company in Japan (Hales *et al.,* 1990). From 1977 to 1984, Toyota Company employs the QFD technique until it spreads out in the area of product design to meet the user's needs (Prasad *et al.*, 1998). In the past, QFD has been successfully adopted to design and develop technical specifications of new products, including improving existing products in the area of industries and business, such as robotics, automobile, aerospace, manufacturing, software, communication, information technology, transportation, and others (Mardia *et al.*, 1979; Chen *et al.*, 2005; Bhattacharya *et al.*, 2005; Haghiac *et al.*, 2005; Miller *et al.*, 2005; Lang *et al.*, 2006; Zheng *et al.*, 2006). In the literature, there are only a small number of robot designs using the QFD technique. QFD was employed to improve the quality of two mechanical robots; 3P Cartesian robot, which has three degrees of freedom and 6R PUMA robot by Koyarem *et al.* (2008). Sorensen also applied the QFD technique in the conceptual and user-concentric design for a plant nursing robot (Sorensen *et al.*, 2009). From the literature, such a systematic QFD method is suitable to match the robot designs to the user's requirements. This paper presents the QFD technique to design an autonomous underwater robot focusing on the Thai Navy military tasks. The Thai Navy has three main routine tasks, (i) underwater surveys under the annual plan in order to conserve the environment and underwater resources, (ii) military diving training, and (iii) inspection of underwater ship structure to find any water leakage. In section 2, the QFD implementation in the autonomous underwater robot design is explained briefly and section 3 describes its results.

2. Materials and Methods

QFD is a systematic design technique, which is efficiently in developing a new product or improving the existing product's quality in accordance to the customer's or user's requirements. It translates the user's requirements into the engineering or technical design parameters. The detail process of QFD can be found in a great number of reference papers or textbooks (Akao *et al.*, 1990; Chan *et al.*, 2005). The QFD process for design and development of an autonomous underwater robot is briefly described below.

2.1 Step 1: User identification

This first step identifies the users, who are directly involved in the employment of the autonomous underwater robot in the Thai Navy. In principle, an interview of 20-30 users is enough as they are representative of 90-95% of the whole user requirements (Chen *et al.*, 2004; Griffin *et al.*, 1993).

2.2 Step2: User requirements

This step surveys the user requirements or voices of users, which have to be translated into the technical design parameters of the autonomous underwater robot.

2.3 Step 3: Prioritizing user requirements

This step assigns the relative importance rating to each user requirement by using a 5-point scale defined as follows: 1 = not at all important, 2 = not very important, 3 = fairly important, 4 = very important, and 5 = extremely important (Kondoh *et al.*, 2007). This step shall be done by Equation 1:

$$I_r = \sum_{j=1}^{C} I_{rj} / C \ ; r = 1, 2, 3, \ldots, R \quad (1)$$

where C is the number of users, Irj is the importance rating of the user requirement (j), R is number of requirements, and I_r is the average importance rating for X_r user requirement. Table 1 shows an example of the relative importance ratings based on user assessments.

Table 1. Example of relative importance ratings based on user assessments with *: User 1 of *n* interviewed users , **: Rating of user 1; and ***: Importance ratings are calculated according to Equation 1.

	Importance ratings				Average importance ratings
Requirement	U_1^{*}	U_2	U_3	$\ldots U_{36}$	I_r^{***}
X_r	I_{r1}^{**}	I_{r2}	I_{r3}	$\ldots I_{r36}$	…………
X_1	5	5	5	4	5
X_2	5	4	3	1	3.9
X_3	5	3	3	5	5
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
$..X_{36}$	5	5	4	5	3.5

2.4 Step4: Identification of design parameters

In this step, the design parameters were identified relatively to the user requirements by a broad range of technical experts shown in Table 2.

2.5 Step 5: Determination of relationships

In this step, the relationships between the user requirements and the identified design parameters were determined by experts listed in Table 2. The degree of relationships (D_r) is set to three levels as follows: strong relation = 9, normal relation = 3, and weak relation = 1.

2.6 Step 6: Correlation between the design parameters

This step determines the correlation between the design parameters by the experts. The degree of correlation is set as follow: ++ = strong positive, + = weak positive, blank = no correlation, - = weak negative, -- = strong negative. This correlation sits in the top of Table 5. The important rank of the design parameters in the bottom of the Table 5 is calculated by using hierarchical clustering as illustrated in Equation 2. It was employed to assign the design parameters into k different groups of importance rankings (*IRank*).

$$IRank = \frac{R_{s,n} - \min}{R} / (k) \tag{2}$$

where R is the range = max-min; max is the maximum value of ($D_{r,n}$), and min is the minimum value of all raw scores ($D_{r,n}$), and

$$k = \sqrt{\frac{n}{2}} \quad ; n = \text{total number of design parameters}$$

$$R_{s,n} = \sum_{j=1}^{m} I_{rj} D_{r,n} \tag{3}$$

where I_{rj} is the average importance rating of user requirement m (m = 1-36) and $D_{r,n}$ is the degree of relationship between user requirement m and design parameter n (n =1-32).

3. Results

3.1 User identification

Thirty underwater robot users in the Thai Navy Office of Naval Research and Development were identified. They were interviewed regarding to their requirements in employing the underwater robot in their three main tasks.

3.2 Identification of user requirements

User requirements were identified by using the literature reviews in the area of underwater robotics, users' comments and the suggestion from the experts listed in

Table 2. Names, affiliations and field of expertise of experts involving in design parameters identification and relations determination between user requirements and technical characteristics.

Names and Affiliations		Fields of Expertise
Assist. Prof. Dr. kridiwat Sutivary	Naval Research & Development Office	Military underwater applications
Assist. Prof. Dr .Keartisak Sriprateep	Department of Manufacturing Engineering, Faculty of Engineering, Mahasarakham University	Industrial design and product optimization
Assist. Prof. Dr.Theerayuth Chatchanayuenyong	Department of Mechatronics Engineering, Faculty of Engineering, Mahasarakham University	Underwater robot design and system integration
Assist. Prof. Dr. Worawat Sa-ngiamvibool,	Department of Electrical Engineering, Faculty of Engineering, Mahasarakham University	Control system design
Assoc. Prof. Dr. Anan Suebsomran	Department of Mechanical Engineering, Faculty of Industrial Education, King Mongkut's Institute of Technology.	Mechanical and System Design
Sir Rene Pitayataratorn	Centre of Excellence in Embedded Development (CEED), Khon Kaen University	Embedded System Design
Assist. Prof. Dr. Korntham Sathirkul	Department of Science Service, Ministry of Science and Technology.	Control System and Mechanical Design
Assist. Prof. Traizit Benjaboonyazit	Thai-Nichi Institute of Technology	QFD expert
Prof. Dr. Sorakit Srikasem	Royal Thai Air Force Academy	Electronics and Communication System design

Table 3. Six categories of user requirements.

Main categories	User Requirements, X_r, r = 1,…, 36
1. Operating Capacity	(1.1) Operating depth up to 10 meters, (1.2) Underwater standstill, (1.3) Able to record video, (1.4) Able to track ship bottom, (1.5) Long operating time, (1.6) Low operating speed
2. Operating Function	(2.1) Operate remotely with cable, (2.2) Operate remotely with radio, (2.3) Autonomous control, (2.4) Easy to control, (2.5) Easy to service, (2.6) Failure self-buoyancy, (2.7) Able to work during night time
3. Economy	(3.1) Low operation costs, (3.2) Low energy consumption, (3.3) Easy to transport, (3.4) Low cost control system
4. Environment	(4.1) Avoids damage to the underwater plants, (4.2) Avoids damage to animals, (4.3) Avoids water polluting, (4.4) Quiet, (4.5) Use renewable energy
5. Operating Safety	(5.1) Safety when transport, (5.2) Fail safe remote surveillance, (5.3) Safety when water leakage
6. Design	(6.1) Self–navigation, (6.2) Easy to add equipment, (6.3) Look beauty, (6.4) Well-managed power supply, (6.5) Structure adjustable to balance the hull, (6.6) Obstacle avoid, (6.7) Light weight, (6.8) Small size, (6.9) Move four degree of freedom, (6.10) Real time video monitoring, (6.11) Use resistance-to-corrosion material

Table 2. The requirements were grouped in six main categories as shown in Table 3.

3.3 Prioritizing user requirements

The user requirements shown in Table 3 were given their individual important ratings and then the average important ratings were calculated in accordance as Equation 2 and put in Table 5. The average important ratings for X_r requirement shown in Table 1 were sorted in descending order and illustrated in Figure 1.

3.4 Selected design parameters

The 32 design parameters identified by the experts are depicted in Table 4. They were grouped in six categories corresponding to the user requirements.

3.5 Relationship rankings

The matrix relationship between user requirements and design parameters is shown in Table 5. Each user's requirement relates to a number of design parameters.

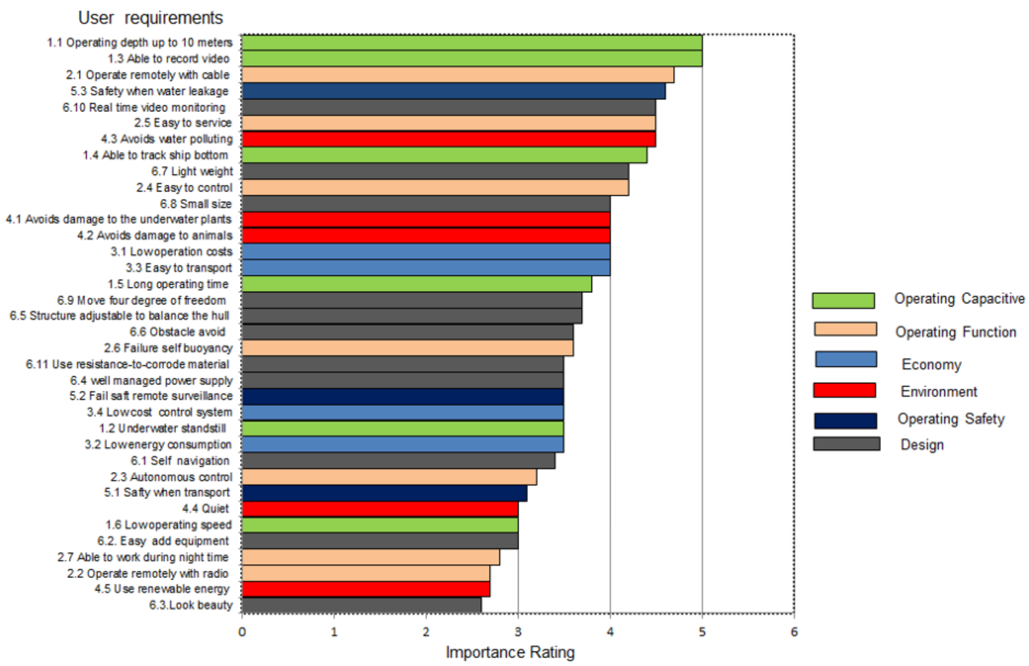
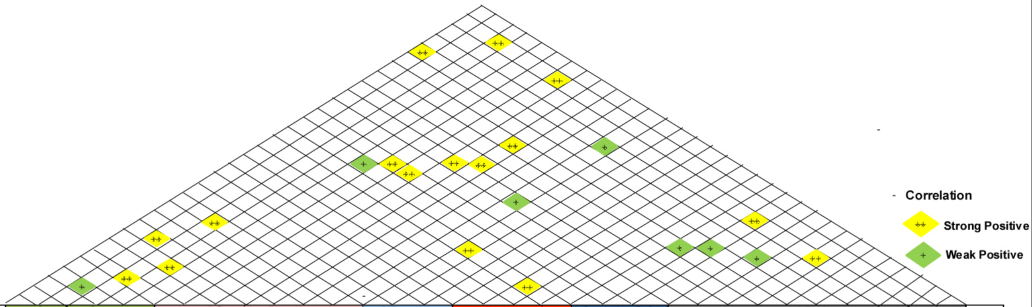


Figure 1. Average importance ratings for the *R* user requirements shown in the horizontal bars. The shading of the bars indicates the six main categories.

Table 4. Selected design parameters corresponding to the six main categories of user requirements.

	Design Parameters	Explanation
1. Operating Capacity	1.1 10-Meter Robot Structure	Structure of the robot can operate underwater up to 10-meter depth.
	1.2 Depth Sensor	Have a depth sensor to measure the robot depth from water surface.
	1.3 Underwater Camera	Have an underwater camera to record photo and video.
	1.4 Ultrasonic Sensor	Have an ultrasonic sensor to measure robot height from water bottom.
	1.5 Power Supply Management	Have well power supply management for equipment inside the robot such as camera, sensor, controller, etc.
2. Operating Function	2.1 Remote Cable Operate	Can control and monitor the robot remotely via cable.
	2.2 Remote Radio Control	Can control and monitor the robot remotely via radio frequency (RF) signal.
	2.3 Autonomous Control Algorithm	Have a control algorithm, which enables the robot to move autonomously.
	2.4 Graphic User Interface	Have graphic user interface between user and robot.
	2.5 Equipment Module Design	Equipment inside the robot is designed in module for easy service purposes.
	2.6 Self Buoyancy System Design	The robot can buoy by itself when it is out of service.
	2.7 Underwater Lights	Have underwater lights for navigation purpose.
3. Economy	3.1 Low Energy Consumption	Use low energy consuming equipment.
	3.2 Equipped With Eyebolts & TransportWheel	The robot can be transported easily with eyebolts and wheel.
	3.3 Low Cost Controller	Use low cost controller.
4. Environment	4.1 Equipped With Thruster Guards	All thrusters are equipped with guard for protection purpose.
	4.2 Use Clean Energy	Use clean energy to conserve environment.
	4.3 Use Low Noise Electric Motor	Use low noise electric motor to avoid nuisance sound.
	4.4 Use Rechargeable Battery	Use rechargeable battery.
5. Operating Safety	5.1 Main Power Safety Switch	Have main power switch to shut down all equipment in case of accident.
	5.2 Remote Surveillance Design	The robot can be shut down all systems remotely.
	5.3 PressureHull	The robot's hull is pressurized to prevent water leakage.
6. Design	6.1 Compass Sensor & Vertical Gyroscope	The robot is equipped with compass sensor and vertical gyroscope.
	6.2 Open Frame Structure Design	The robot structure has an open frame design, which can be equipped with external sensor easily.
	6.3 BeautifulHullFormDesign	The hull form of robot is well designed and looks beautiful.
	6.4 Detail Power Distribution Planning	The power distribution for equipment inside the robot is well-managed.
	6.5 Adjustable Buoyancy Components	The buoyancy level of robot can be adjusted with its components.
	6.6 Use Strong But Light Weight Material	The robot structure is made of not only light weight but also strong material.
	6.7 Small Overall Size	The overall size of robot is small to be easily transported.
	6.8 Configuration Design	The robot is well configured to make it balance in all dimensions.
	6.9 Communication System Design	The user can communicate with the robot for controlling and monitoring purposes.
	6.10 Use Resistant To Corrosion Material	The material for underwater pressure hull must not only be able to withstand high external pressure, but must also withstand the environment (Ross *et al.*, 2006)

Table 5. Tables in the QFD analysis of the relationships between user requirements and design parameters.



			1.Operating Capacity					2.Operating Function							3.Economy			4.Environment				5.Operating Safety			6.Design										
		Importance Rating	1.1 10-MeterRobotStructure	1.2 DepthSensor	1.3 UnderwaterCamera	1.4 UltrasonicSensor	1.5 PowerSupplyManagement	2.1 RemoteCableOperate	2.2 RemoteRadioControl	2.3 AutonomousControlAlgorithm	2.4 GraphicUserInterface	2.5 EquipmentModuleDesign	2.6 SelfBuoyancySystemDesign	2.7 UnderwaterLights	3.1 LowEnergyConsumption	3.2 EquippedWithEyebolts&TransportWheel	3.3 LowCostController	4.1 EquippedWithThrusterGuards	4.2 UseCleanEnergy	4.3 UseLowNoiseElectronic Motor	4.4 UseRechargeableBattery	5.1 MainPowerSafetySwitch	5.2 RemoteSurveillanceDesign	5.3 PressureHull	6.1 CompassSensor&VerticalGyroscope	6.2 OpenFrameStructureDesign	6.3 BeautifulHullFormDesign	6.4 DetailPowerDistributionPlanning	6.5 AdjustableBuoyancyCorponents	6.6 UseStrongButLightWeightMaterial	6.7 SmallOverallSize	6.8 ConfigurationDesign	6.9 CommunicationSystemDesign	6.10 UseResistanceToCorrosionMaterial	SumOfHorizontalScore
1.Operating Capacity	1.1 Operating depth up to 10 meter	5	9	9		3	9	3	1	9			9		9	3		1	9		9			1		3	3		9	1	3	1		9	113
	1.2 Underwater standstill	3.9		9		3	9			9			9		9		9		3								9	9	9		9	3		3	102
	1.3 Able to record video	5			9						9										3				9						1		9	3	43
	1.4 Able to track ship bottom	4.4	3	9	9	9	9	9	1	9	3			9		1		3		3	3	3			9	9					1				102
	1.5 Long operating time	3.8					9			9					9													9			9		9	3	57
	1.6 low operating speed	3	1	9		9	9			9			1				9				9					3		9	9		9	9			95
2.Operating Function	2.1 Operate remotely with cable	4.7		9		3		9			9					9	9					9			9										66
	2.2 Operate remotely with radio	2.7		9		9			9		9					9	9					9			9							9			81
	2.3 Autonomous control	3.2		9		9				9	9			9		9	9					9			9	9					3				93
	2.4 Easy to control	4.2		9				9		9	9			9			9								9	9					3				75
	2.5 Easy to service	4.5		9			3					9						9						3		9						9		9	60
	2.6 Failure self buoyancy	3.6	3										9														1		9					3	25
	2.7 Able to work during night time	2.8		9	9	9	9							9											3						9				57
3.Economy	3.1 Low operation costs	4	1				9								9		3				9													3	34
	3.2 Low energy consumption	3.5					3								9	9					3														24
	3.3 Easy to transport	4	9				9							1		9		9				9								9	9	9		3	76
	3.4 Low cost control system	3.5				9											9								9	9							9	9	54
4.Environment	4.1 Avoids damage to the Underwater plants	4		9		9		3	1	9				9			9	9				1			9										68
	4.2 Avoids damage to animals	4		9		9		3	1	9				3			9	9				1			9										62
	4.3 Avoids water polluting	4.5								9							9	3	9						9									3	42
	4.4 Quiet	3													3					9												3			15
	4.5 Use renewable energy	2.7					9								3		3				9							3							27
5.Operating Safety	5.1 Safty when transport	3.1	9					3										9				9					9			9	9			3	60
	5.2 Fail saft remote surveillance	3.5											9										9						3			3			24
	5.3 Safety when water leakage	4.6					3	3		9			3				9					3		9					1	9	3			9	61
6.Design	6.1 Self navigation	3.4		9		9		9		9	9			1			9								9								9		73
	6.2 Easy to add equipment	3	3				3				9						9									9	3					3		3	42
	6.3 Look beauty	2.6	9											1		1										1	9			9	9	3		9	51
	6.4 Well-managed power supply	3.5					9										9											9							27
	6.5 Structure adjustable to balance the hull	3.7	9						3	3			9		3						3		9		9				9			9		3	69
	6.6 Obstacle avoid	3.6		9	9	9		9		9	1			9											9					9					73
	6.7 Light weight	4.2	9												3		9			3	3			3					3	9	9			1	52
	6.8 Small size	4	9	3				9		9							9									3			3		9	3			57
	6.9 Move four degree of freedom	3.7				9		9	9	9															9	9					9	9	3		75
	6.10 Real time video monitoring	4.5			9			9	9	9	9			9			9																9		72
	6.11 Use resistance-to-corrosion materia	3.5	9												3							9		3					1					9	34
	Raw score		311	493	183	386	381	355	127	585	293	40.5	194	262	233	185	604	208	97.2	52.8	195	226	64.8	83	500	277	114	136	216	204	376	259	193	333	2141
	Relative %		4%	6%	2%	5%	5%	4%	2%	7%	4%	0%	2%	3%	3%	2%	7%	3%	1%	1%	2%	3%	1%	1%	6%	3%	1%	2%	3%	2%	5%	3%	2%	4%	100%
	IRank		3	4	2	3	3	3	2	5	3	1	2	3	2	2	5	2	1	1	2	2	1	1	4	3	2	2	2	2	3	3	2	3	79

Summing of the raw relationships for each user requirement in horizontal row shows the three highest value results; 113, 102, 102, and 95 for "operating depth up to 10 m", "underwater standstill", "able to track ship bottom", and "low operating speed", respectively. The three lowest values are 15, 24, 24, and 25 for "quiet", "fail-safe remote surveillance", "low energy consumption", and "failure of self-buoyancy", respectively.

The design parameters, which have got the three highest importance ranking (*IRank* = 5, 4, and 3), as illustrated in Figure 2 were Low Cost Controller, Autonomous Control Algorithm, Compass Sensor Vertical Gyro, Depth Sensor, Small Overall Size, Supply Management and Ultrasonic Sensor. On the other hand, the design parameters, which have got the two lowest importance ranking (*IRank* = 1) were Equipment Module Design, Use Clean Energy, Use Low Noise

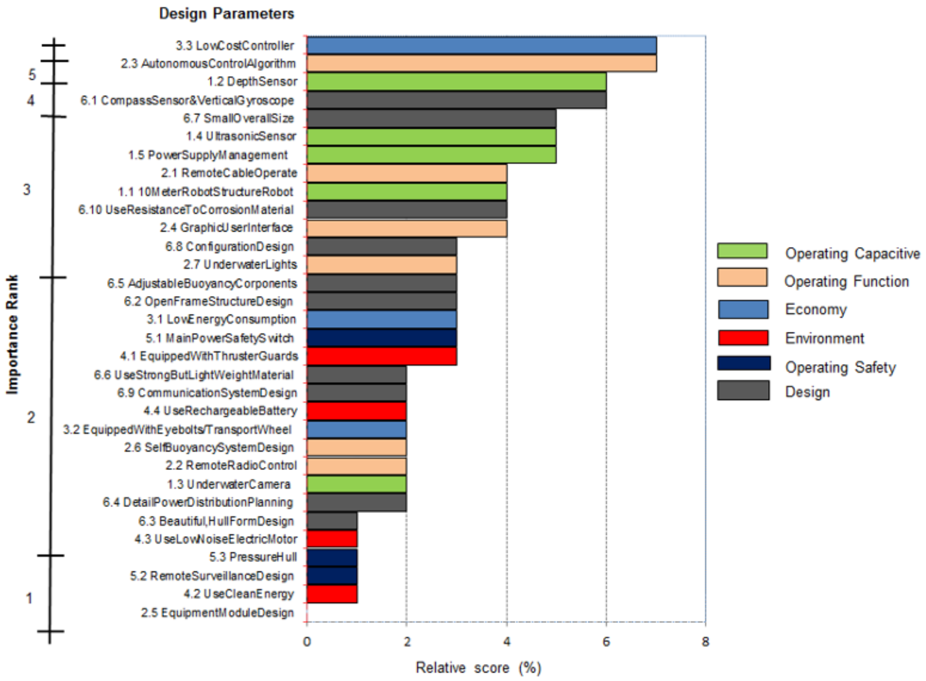


Figure 2. Design parameters plotted in order according to the relative scores from Table 5. The shading of the bars indicates the six main categories.

Electric Motor, Remote Surveillance Design, Pressure Hull and Beautiful Hull Form Design.

3.6 Design parameter correlations

The design parameter correlations sit on the top of Table 5. The design parameters have positive correlations or none. No negative correlation exists.

4. Discussion

The result in Table 5 concludes the relationships between 36 user requirements and 32 design parameters; including their significances in terms of importance rating and importance rank (*IRank*). Each design parameter has at least one relationship with the user requirements, while each user requirement has three or more relationships with the design parameters. No unfilled columns or rows was found in the table, hence no irrelevant or redundant parameters existed (Verma *et al.*, 1998). Each user requirement was responded by at least three design parameters. Regarding the results in Section 3.5, three highest horizontal summing scores are operating depth up to 10 m (113), underwater standstill (102), able to track ship bottom (102), and low operating speed (95). The "operating depth up to 10 m" got the highest score both in the horizontal summing and user important rating (5) since most of the Thai Navy Military's routine task operates at approximately 10 meter depth. The "underwater stand still" and "able to track ship bottom" got the same 2nd highest score (102) with their corresponding high important rating of 3.9 and 4.4, respectively, because the three main routine tasks of the Thai Navy need the ability to standstill underwater during its surveying mission and at the same time able to inspect the underwater ship structure with tracking capability. The 3rd highest score parameter is "low operating speed" (95), which is the suitable speed for survey, inspection and training tasks. The "quiet" parameter got the lowest horizontal summing score. This corresponds to its low importance rating (3.0). This user requirement was responded by three design parameters and could be handled easily by the Use Low Noise Electric Motor design parameter.

Figure 1 depicts the comparison bars of the user requirements. The highest important rating of the user requirements are "operating depth up to 10 m" and "able to record video" while the lowest-important-rating user requirement is "beauty". This result agrees with the Thai Navy tasks, which need video recording during three main tasks while the robot appearance is insignificant.

The design parameters, which obtained high important ranking shown in Figure 2, mainly focus on the autonomous control (Autonomous Control Algorithm) and its relative parameters (Compass Sensor Vertical Gyroscope and Depth Sensor). The Equipment Module Design parameter obtained unexpectedly low important ranking. This parameter got a strong relationship to the user requirement "easy to service", which has a high important rating of user requirement (4.5). It is related to only one user requirement. The other low important ranking design parameters are Pressure Hull and Remote Surveillance Design. These two parameters in the user's point of view are not important but they might get higher relative score in the engineering point of view.

According to the results, it can be seen that all the users' requirements have been ranked in accordance as their relative scores and responded by the design parameters. Hence, the design parameters with high importance rating and high important rank could be selected and included in the prototype designed robot to reflect the expectations and satisfactions of the users.

Table 6 maps all design parameters to expected parameters, which tend to be employed in the final detailed specifications of the robot. Finally, these detailed specifications of QFD underwater robot illustrated in Table 5 have to be derived in a blueprint and the constructed robot must be tested in the real situation to prove its performance. Figure 3 depicts a conceptual draft design of the autonomous underwater robot.

5. Conclusions

The QFD method was adopted to develop a conceptual design of an autonomous underwater robot for Thai Navy Military tasks. It provided a systematic procedure to obtain the user requirements and derived the relating design parameters, which has never been done before in the literature of

Table 6. Mapping between design and expected parameters

Item	list	Design parameters	Expected parameters
1	2.3	Autonomous Control Algorithm	Conventional PID and intelligent control
2	3.3	Low Cost Controller	Micro-controller
3	1.2	Depth Sensor	Pressure sensor
4	5.1	Compass Sensor & Vertical Gyroscope	Compass sensor, vertical gyroscope
5	1.4	Ultrasonic Sensor	Fish finder sonar sensor
6	1.5	Power Supply Management	Three power supply modules; controller power supply, sensor power supply and motor driver power supply modules
7	5.7	Small OverallSize	Not bigger than 120x120x120 cm
8	1.1	10-meter Robot Structure	Aluminum alloy
9	2.1	Remote Cable Operate	0.9 mm^2 4-cores cable
10	2.4	Graphic User Interface	Visual basic
11	5.10	Use Resistance To Corrosion Material	Aluminum alloy
12	2.7	Underwater Lights	Tungsten halogen lamp
13	3.1	Low Energy Consumption	Controller low power supply, sensor low power supply and motor driver low power supply modules
14	4.1	Equipped With Thruster Guards	Aluminum thruster guards
15	5.1	Main Power Safety Switch	Safety switch
16	5.2	Open Frame Structure Design	Aluminum open frame structure
17	5.5	Adjustable Buoyancy Components	Equipped with buoyancy components, e.g. pressurizable plastic tube, foam
18	5.8	Configuration Design	3-D Balancing shape designed with SolidWorks
19	1.3	Underwater Camera	Digital camera installed inside pressurized hull
20	2.2	Remote Radio Control	Not installed, since it is not practical when the robot is underwater.
21	2.6	Self Buoyancy System Design	Buoyancy force > gravitational force design
22	3.2	Equipped With Eyebolts & Transport Wheel	Eyebolts and transport wheels
23	4.4	Use Rechargeable Battery	Use rechargeable battery
24	5.4	Detail Power Distribution Planning	Three power supply modules; controller power supply, sensor power supply and motor driver power supply modules
25	5.6	Use Strong But Light Weight Material	Aluminum alloy
26	5.9	Communication System Design	RS232 cable
27	4.2	Use Clean Energy	Use rechargeable battery
28	4.3	Use Low Noise Electric Motor	Electric trolling motor
29	5.2	Remote Surveillance Design	Signal sending via RS232 cable
30	5.3	Pressure Hull	Pressurized robot hull
31	5.5	Beautiful Hull Form Design	Balancing-shape hull form designed with Solidworks
32	2.5	Equipment Module Design	Equipment designed in modules and connected to one another via connectors

underwater robot designs. The important user requirements extracted from the QFD method are: (1) able to record video, (2) operating depth up to 10 meters, (3) operate remotely with cable, and (4) safe during water leakage. The low important rating user requirements include: (1) beauty, (2) use renewable energy, (3) operate remotely with radio, and (4) able to work during night time.

The important design parameters derived from the user requirements are: (1) Low Cost Controller, (2) Autonomous Control Algorithm, (3) Compass Sensor Vertical Gyroscope, and (4) Depth Sensor. The low important-ranking design parameters include: (1) Equipment Module Design, (2) Use Clean Energy, (3) Use Low Noise Electric Motor, (4) Remote Surveillance Design, (5) Pressure Hull, and (6) Beautiful Hull Form Design. Mapping between the design and expected parameters is concluded in Table 6, while the conceptual drafting design of the QFD robot is illustrated in Figure 3. The high important rating and high important rank design parameters could be selected and included in the prototype designed robot to meet the expectations and satisfactions of the users.

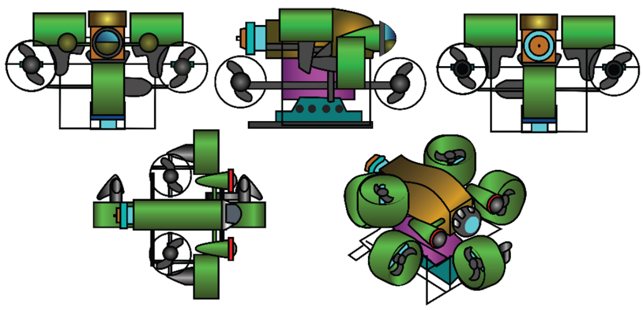


Figure 3. A conceptual drafting design of an autonomous underwater robot.

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