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A User Requirement-driven Approach Incorporating TRIZ and QFD for Designing a Smart Vessel Alarm System to Reduce Alarm Fatigue

Fan Li¹, Chun-Hsien Chen¹, Ching-Hung Lee² and Li-Pheng Khoo¹

¹(School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore)

²(School of Public Policy and Administration, Xi'an Jiaotong University, Xi'an, China)
(E-mail: leechinghung@xjtu.edu.cn)

Alarm fatigue is a critical safety issue, as it can increase workload and impair operators' situational awareness. This paper proposes a design methodology to enhance the interaction between alarm systems and operators. Through input from VTS personnel as the fundamental design requirements, a user requirement-driven design framework is proposed. It integrates quality function deployment, the theory of inventive problem solving, and software quality characteristics into three design phases. In Phase I, user requirements are obtained from the analysis of current working processes. Phase II investigates the specific non-functional design requirements of vessel alarm systems and the contradictions. In Phase III, the innovative principles generated with the contradiction matrix were analysed. A case study was conducted to verify and illustrate this framework, resulting in a conceptualisation design of a smart vessel alarm system.

KEY WORDS

1. Vessel Traffic Service (VTS).
2. Alarm fatigue.
3. Quality Function Deployment (QFD).
4. Theory of inventive problem solving (TRIZ).

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1. INTRODUCTION. A Vessel Traffic Service (VTS) is a shore-based service (SOLAS, 2002) that provides information services, navigational assistance and traffic organisation services to vessels entering or passing a designated area (Xu et al., 2015; Hughes, 1998; 2009; Mansson et al., 2017). VTS operations are complex and dynamic, resulting in a high possibility of human error (Filipowicz, 2004). Hence, a number of decision support systems have been implemented to assist VTS Operators (VTSOs) (Kao et al., 2007; Li et al., 2015; Babu and Ketkar, 1996). The traffic alarm system of a Vessel Traffic Management System (VTMS) (hereafter, we also use the term Vessel Alarm System (VAS), to describe the same concept) is a basic decision support system for alerting VTSOs to abnormal traffic situations, such as grounding and near collision (Kao et al., 2007;

Su et al., 2012; Lee et al., 2014). It warns operators about a situation that is abnormal and serves as the event log. In general, alarm systems can improve VTSOs' performance by enhancing situation awareness (Li et al., 2017). However, less than perfect alarm systems may induce alarm fatigue, a phenomenon of distrusting or neglecting alarms.

In general, alarm fatigue is caused by floods of false or nuisance alarms (Winters et al., 2018). Nowadays, many advanced technologies have been implemented into alarm systems, leading to highly sensitive alarm systems which generate too many alarms. The Engineering Equipment and Materials Users Association (EEUMA) suggested that the optimal number of alarms per hour is six (Hollifield et al., 2013), while in practice, VTSO in busy traffic areas receive far more than six alarms. Most alarms are nuisance alarms that induce the "crying wolf" effect (Izadi et al., 2009). Alarm fatigue has been identified as the top risk factor in the safety and security industry (Rayo and Moffatt-Bruce, 2015). Recently, increasing academic research has been focussed on addressing alarm fatigue (Bustamante et al., 2007). Many techniques, such as adaptive thresholds, process data filtration, alarm delay and alarm dead bands have been studied to reduce alarm fatigue (Izadi et al., 2009). These studies have focused on achieving these techniques. However, only a few studies have focused on the techniques required from the perspective of user requirements.

A user requirement-driven design, which considers human limitations and User Requirements (URs), may be beneficial in reducing alarm fatigue. URs have been widely accepted as an important source to subsequently obtain design metrics and specifications in the early stages of product concept design and conceptualisation of technology innovation (Wang and Hsieh, 2018). The alarm system design guidebook, which was released by the EEUMA (Hollifield et al., 2013), pointed out that alarm systems should be 'context-sensitive' and take account of human limitations during the design phase (EEUMA, 1999). Moreover, a study conducted in three VTS centres found that it is critical to provide the right information according to users' needs (Praetorius and Lützhöft, 2012). Therefore, an integrated UR-driven framework is introduced in this paper to improve alarm systems. To achieve this aim, several challenges remain to be solved.

First, the quality and completeness of URs are hard to control. Unlike common products, VAS have relatively low user numbers. Eliciting URs from limited users is challenging. Second, Design Requirements (DRs) of alarm systems remain to be investigated. And lastly, there are some contradictions among DRs. For example, to maintain the sensitivity of the alarm system, the threshold should be set low. However, the threshold should also be set high to reduce the number of nuisance alarms. A balance needs to be struck.

Accordingly, PQT (Process-based elicitation of URs, Quality Function Deployment (QFD)-enabled selection of DRs, and the Theory of Inventive Problem Solving (TRIZ)-based generation of innovative solutions), which is named by combining the initial letters of each phase, is proposed to reduce alarm fatigue. Then, a case study on the alarm system of the VTS centre in Singapore is conducted to illustrate the URs-driven framework.

2. THEORETICAL BACKGROUND.

2.1. QFD application in the maritime industry. QFD is a quality improvement method which focuses on meeting customer needs. It provides a set of matrices that link inputs to outputs. QFD has been applied in a wide variety of fields, such as consumer products, military needs and emerging technology products in recent years (Lee et al., 2015; Zhang et al., 2014; Yan et al., 2005). Moreover, it has been adopted to improve the maritime

industry. Lam and Lai (2015) developed an Analytical Network Process (ANP)-QFD model incorporating the ‘voice’ of customers to improve marine environmental sustainability.

QFD can transform qualitative user demands into quantitative parameters. Due to its valuable advantages in dealing with URs, the authors adopted QFD as a critical part of the PQT framework. However, QFD struggles to provide designers with innovative ideas because of its internal defects (Zhang et al., 2014) in that there is a lack of effective solutions to eliminate the contradictions, the large size of the matrix may cause complexity in design, the incompleteness of customer requirements and research subjectivity maybe argued, and there is a lack of a systematic knowledge base for inspiring resolutions.

One way to remedy the internal defects of QFD is combining it with other methods. The authors attempted to integrate QFD with TRIZ, as TRIZ has high efficiency and ability in eliminating contradictions.

2.2. *Theory of Inventive Problem Solving (TRIZ)*. Altshuller et al. (1999) proposed TRIZ after analysing more than two million patents from over 40 years. In comparison with traditional processes of solving problems, TRIZ reformulates specific problems into generic ones, and then uses TRIZ tools to seek generic solutions. In this study, the 40 Inventive Principles are adopted due to their efficiency and ability in eliminating contradictions. Contradictions, which refer to the classical engineering “trade-offs”, are at the heart of many problems. The “trade-off” means that when something gets better, something else gets worse (Lee et al., 2019). The engineering contradiction matrix can be used to determine the Inventive Principles to solve specific contradictions.

Altshuller et al. (1999) summarised 39 engineering parameters in the contradiction matrix. With the wide application of TRIZ, researchers tried to translate engineering parameters into other kinds of parameters, such as service parameters. Chang and Lu (2009) transformed engineering parameters into service parameters. Coelho (2009) matched engineering parameters to human factors parameters. Interactive parameters and principles are introduced in the study of Filippi and Barattin (2015). Several versions of software parameters can also be found in Kluender’s study (2011). Mann’s study (2004) added nine parameters to the original engineering list. Researchers have also made efforts in applying the 40 inventive principles in the context of software and computing. Filippi and Barattin (2015) compared engineering inventive principles with interactive design principles.

2.3. *The integration of QFD and TRIZ*. In the application of QFD or TRIZ, one of the recent trends is integrating them to strengthen their strong points and eliminate their defects. Most research studies have used TRIZ to solve engineering characteristic contradictions identified from QFD (Yeh et al., 2011; Yamashina et al., 2002). These studies investigated the applicability and effectiveness of Integrated QFD-TRIZ (IQT) in design and development of tangible products (Zhang et al., 2014). However, the usability of IQT in intangible product design, such as service design and software design, has received limited attention (Lee et al., 2015; Wang et al., 2017).

3. **UR-BASED DESIGN FRAMEWORK FOR VESSEL ALARM SYSTEM.** In this study, an innovative and integrated design framework named PQT (combining the initial letters of each phase) was proposed based on quality characteristics of software, QFD and TRIZ. Figure 1 illustrates the framework of PQT, which includes three main phases: (1) Process-based elicitation of URs, (2) QFD-enabled selection of DRs and (3) TRIZ-based generation of innovative solutions. In the first phase, the work logic of alarm systems

Figure 1. PQT Framework of user requirement-driven design for Vessel Alarm System.

and operational process are investigated through field observation and Standard Operational Procedures (SOP) analysis. Based on the operational process of alarm systems, corresponding initial URs can be elicited through unstructured interview. To prioritise initial URs, experts are recruited to pre-screen and evaluate the initial URs. In the second phase, non-functional requirements of alarm systems are analysed to determine the candidate DRs. QFD is adopted in the second phase to identify critical DRs from the candidate DRs. In the solutions generation phase, selected DRs are translated into TRIZ parameters to find the suggested principles. Finally, the approved solutions are developed following the TRIZ principles. The novelty of this research is the development and demonstration of a UR-driven design framework using integrated TRIZ, QFD and software characteristics for designing a new VAS.

3.1. Phase I: Process-based elicitation of user requirements. As one of the most important elements of QFD (Dieste et al., 2008), URs have a crucial impact on the success of designing new products (Wang et al., 2002). Conventional QFD approaches assume that URs are sufficient and correct. Nevertheless, how to collect appropriate URs is beyond the concern of conventional QFD. Therefore, we propose a process-based method to obtain meaningful URs.

Among various methodologies on UR elicitation, the expert interview is the most widely used approach due to its convenience and adaptability (Moore and Shipman, 2000). Nevertheless, without appropriate guidance, the fulfilment of URs cannot be guaranteed. To overcome this problem, operational processes of alarm systems are analysed in this study. The operational processes, which provide information about work practices, even practices that end users are not aware of, can be utilised to guide the recall of interviewees (Moore and Shipman, 2000). Therefore, the authors proposed process-based elicitation of URs, as illustrated in Figure 2.

Field observation and SOP analysis can be conducted to generate the operational processes for specific VAS. Designers observe how operators use the alarm system and discuss with experts during the field observation. The unstructured interview is designed based on the operation process diagram to explore in-depth insight into users' experiences. The

Figure 2. General processes of Phase I.

Figure 3. General processes of Phase II.

entire interview should be videotaped and include audio. All videotapes are reviewed after the interviews gather initial URs. Final URs are obtained by eliminating, combining and translating initial URs. Finally, experts are invited to rate the relative importance weights of final URs by utilising a five-point linear numeric rating scale. The final URs and the corresponding numeric ratings are utilised as the inputs of QFD.

3.2. Phase II: QFD-enabled selection of design requirements. Figure 3 illustrates the procedures of identifying critical DRs of the VAS, namely Phase II. This phase includes a

Table 1. The quality characteristics of software (Şen and Baraçlı, 2010).

Usability	Functionality	Reliability	Maintainability	Efficiency
Understandability	Suitability	Recoverability	Testability	Time behavior
Operability	Security	Maturity	Stability	Resource behavior
Learnability	Interoperability	Fault tolerance	Changeability	
	Compliance		Analysability	
	Accuracy			

House of Quality (HoQ) chart (Zhang et al., 2014) to identify critical DRs. The URs elicited from the first step are used as the “whats” along the vertical axis of the chart to construct the HoQ. The importance weights of URs are added along the vertical axis. Along the horizontal axis are the candidate DRs as the “hows”. The candidate DRs are determined through non-functional requirements analysis and alarm systems analysis.

The standard of the International Standardization Organization (ISO, 2007) defines five software quality characteristics, namely usability, efficiency, maintainability, reliability and functionality. These characteristics are consistent with the guidelines on software quality assurance and human-centred design for e-Navigation, which were published by the International Maritime Organization (IMO, 2015). Earlier, Şen and Baraçlı (2010) broke these guidelines down into more specific sub-characteristics to acquire enterprise software selection requirements. The summarised results of quality sub-characteristics are shown in Table 1. In order to get specific DRs of the VAS, we attempted to combine quality sub-characteristics and modules of the VAS. The general VAS involves five modules: signal filter, alarm generation, alarm suppression, alarm shelving and alarm presentation (Figure 4). The signal filter is the master in the alarm system. It performs the role of Sensor Fusion. The alarm general module receives tracks from radar and other track sources. This module maintains separate track tables for all track data sources, and at the same time performs multi-sensor fusion so that all tracks from all sources are merged into integrated tracks. Each integrated track and object are checked against a certain set of alarm trigger protocols. When a rule is violated, an alarm is triggered. Based on the prioritisation policies, the priority level of the alarm is determined. Some alarms with low priority would be suppressed. This procedure is conducted by the alarm suppression. The alarm presentation type is determined by the classification policies. The alarm shelving provides operators opportunities to shelve alarms meeting specific requirements. Shelving provides a controlled mechanism for operators to temporarily remove an alarm.

With the above analysis, the DRs of VAS could be inferred from “module + quality characteristics”. For example, alarm presentation understandability means the readability and informative value of the visual/audio alarm.

The importance of each UR to DR is reflected by the indicators (R_{ij}), placed in the relationship matrix. A rating scale (0-3-5-9) is used to evaluate the relationship (none, weak, moderate and strong) between URs and DRs. The overall importance score of each DR is calculated by the following equation:

$$\text{Absolute importance score of } T_j = \sum_{i=1}^I R_{ij} * U_i, \quad (1)$$

where T_j is the overall score of the j -th DR, U_i is the importance score of the i -th UR, R_{ij} is the score related to the relationship between URs and DRs.

Figure 4. The functions of current vessel traffic alarm systems.

The output of the QFD is a set of ranked DRs that are explicitly linked to URs. The roof indicates the interrelations in DRs. The outputs of Phase II indicate the critical DRs waiting to be improved and the interrelations among DRs.

3.3. Phase III: TRIZ-based generation of innovative solutions. The critical DRs and their interrelations are used as inputs for this phase, which involves DRs classification and TRIZ contradiction analysis. The DRs classification links the critical DRs to corresponding modules of the VAS. TRIZ contradiction analysis provides inventive principles based on the interrelations among the DRs. The combination of QFD and TRIZ makes the development of a contradiction matrix easier than the conventional method. First, the DRs are translated into TRIZ parameters. In this study, TRIZ parameters updated in 2003 (Mann and Dewulf, 2003) are utilised, as this involves most software qualities. Second, the TRIZ matrix is established to generate the innovative principles. Directly applying the original inventive principles in software development is improper and unworkable, as original inventive principles are mainly used in the field of engineering. Therefore, software analogies of TRIZ which were proposed by Rea (2001) are referenced. Finally, principles with high frequency are selected to generate effective solutions for specific problems. Figure 5 illustrates the logic of solution generation.

4. CASE STUDY. A case study was conducted to illustrate the design approach (Peffers et al., 2007), while verifying the proposed framework, through an empirical study. This study was conducted in the Singapore Vessel Traffic Service (VTS) centre. During our field observation, we found that operators tend to ignore most of alarms generated by the present VAS, as they are deemed to be “unhelpful and useless” and interrupt their communication with pilots. As a result, this highlighted two problems of the present VAS,

Figure 5. Solutions generation process of phase III (TP means TRIZ principles).

which are namely *Problem 1*: the inability to reduce the operators' workload effectively in abnormal situations, and *Problem 2*: the presence of multiple false alarms which impedes the operators' situation awareness.

4.1. *Phase I: User requirement analysis of new vessel alarm systems.* Field observation and SOP analysis were conducted to identify the current operational processes. First, operators should make a track assignment for vessels entering the Singapore Strait. Most alarm assignments are associated with one or more warnings. For different vessels, different assignments may be made. Therefore, operators must be familiar with the rules of setting track assignments. Second, operators detect and analyse the triggered alarms. There are two kinds of alarm mode in the VAS, namely visual alarms and audio alarms. After detecting an alarm, operators analyse current conditions and make decisions to deal with this alarm. Then, operators can acknowledge or cancel the audio alarm after correcting the condition that led to the alarm.

To identify the URs, unstructured interviews were conducted. 42 operators (32 males and 10 females) participated in this study. Their average experience was ten years. All interviews were recorded and fully transcribed. Transcribed interviews were coded, resulting in an initial set of 27 codes (see Appendix). The authors translated the 27 codes into seven URs, namely UR₁: accurate alarms, UR₂: effective alarms, UR₃: comfort, UR₄: safety, UR₅: easy to use, UR₆: responsiveness, UR₇: informative alarms. A total of 12 operators determined the importance score on each elicited UR based on the predetermined scheme, such as "5" stands for the greatest importance while "1" represents the least importance. The importance of score and detail description of each UR are also shown in Table 2.

4.2. *Phase II: Design requirement analysis of new vessel alarm systems.*

4.2.1. *Alarm system analysis.* The existing VAS involves three main modules: track assignment module, alarm generation module and alarm presentation module. The functions and description of the current modules are shown in Table 3.

Track assignment module: There are 40 kinds of alarms in this module. Operators analyse vessel information integrated from the Automatic Identification System (AIS), radar,

Table 2. Pre-screened URs by eliminating, combining and translating.

URs	Definition	UR codes	Importance Scores
UR ₁ Accurate alarms	The system provides less false, missed alarms.	1, 2, 12, 19, 20	5
UR ₂ Effective alarms	The system provides less repeat alarms. Operator has enough time to deal with alarms.	3, 26	5
UR ₃ Comfort	The system is comfortable to use. The system style is matched with the VTS console.	5, 6, 7, 8, 16, 10	5
UR ₄ Safety	The system provides human error protection.	9, 11	4
UR ₅ Easy to use	The system provides simple operation. E.g. The alarm messages can be detected easily.	4, 13, 14, 18, 21, 22, 23, 24	4
UR ₆ Responsiveness	The system provides rapid-response.	15	4
UR ₇ Informative alarms	The alarm messages provide enough information.	17, 25, 27	5

Table 3. Current vessel alarm system of Singapore VTS.

Modules	Functions	Description
Track assignment module	Vessel details Vessel alarm determination	Identity area, data area, notifications area Anchor watch, berthing watch, collision watch, domain watch, grounding watch, speed watch
Alarm generation module	Threshold setting	Range
Alarm presentation module	Group vessel alarms Acknowledge alarms Alter option	Grouped by selecting Type, Priority, or None Acknowledge single or multiple alarms, cancel audio alarms Audio and/or visual alert

Closed-Circuit Television (CCTV) and then determine which type of alarm should be assigned to the vessel.

Alarm generation module: Operators can edit the alarm threshold in the “range” section of this module.

Alarm presentation module: Each type of vessel alarm can have both visual and audio alerts. The visual option refers to a configured colour in a shape (square, circle or triangle) around the target vessel. To handle alarms, operators can group alarms by selecting type or priority and then acknowledge or cancel alarms.

4.2.2. *Candidate DRs.* The details of DRs have been published in the authors’ previous paper (Li et al., 2017). Hence, the DRs are not explained in detail in this work.

4.2.3. *Determine the critical DRs.* Figure 6 shows the QFD relationship matrix, which was constructed with the help of VTSOs. Numbers utilised in the QFD matrix, and their corresponding meanings are described as follows: “9” indicates strong correlation; “3”

Figure 6. HoQ of the vessel alarm systems (Li et al., 2017).

denotes ordinary correlation; and “1” represents weak correlation. For example, the UR “accurate alarms” presented a strong correlation to each of the three items “Alarm Trigger Algorithm (ATA) accuracy”, “Sensor accuracy”, and “ATA fault tolerance”. Not only does the alarm trigger algorithm affect the accuracy of generated alarms, the signal which is obtained from the sensor also affects the accuracy of alarms. “Safety” was found to correlate strongly with “System response speed”, as system response speed affects the response ability of the system. If operators had dealt with the alarms, while the system has no response, the situation would be dangerous.

The importance scores are obtained using Equation (1). The final five top-ranked DRs (as shown in Figure 6), including “ATA accuracy” (DR₁: with 192 scores), “Alarm Assignment Rules (AAR) complexity” (DR₂: with 180 scores), “ATA aptness” (DR₃: with 171 scores), “Alarm Presentation (AP) informativeness” (DR₄: with 162 scores), “AP aptness” (DR₅: with 132 scores), are selected that fit best with the URs to improve the VAS.

4.2.4. Investigate the contradictions among DRs. The DRs that have contradictions with the five top-ranked DRs were selected too. The “roof” of the quality house indicates contradictions between DRs, as represented with the symbol “+” in Figure 6. According to the analysis of URs, the accuracy and aptness of generated alarms have to be improved. However, a contradiction exists between “DR₆: ATA complexity” and “DR₃: ATA aptness”. A contradiction is also apparent between “DR₁: ATA accuracy” and “DR₇: ATA efficiency”, as high accuracy requires low time delay, which directly increases the latency

Table 4. The contradictions extracted from QFD.

Modules	The positive qualities	Corresponding negative qualities
Track assignment module	DR ₂ : AAR complexity	DR ₁ : ATA accuracy DR ₃ : ATA aptness
Alarm generation module	DR ₁ : ATA accuracy DR ₃ : ATA aptness	DR ₆ : ATA complexity DR ₇ : ATA efficiency
Alarm presentation module	DR ₄ : AP informativeness DR ₅ : AP aptness	DR ₈ : Readability of alarm messages DR ₉ : AH operability

Table 5. TRIZ-based parameters of this case.

Design requirements	Corresponding TRIZ engineering parameters
DR ₁ : ATA accuracy	#48 Measurement accuracy
DR ₂ : AAR complexity	#45 Complexity
DR ₃ : ATA aptness	#32 Adaptability
DR ₄ : AP informativeness	#11 Amount of information
DR ₅ : AP aptness	#32 Adaptability
DR ₆ : ATA complexity	#45 Complexity
DR ₇ : ATA efficiency	#14 Speed
DR ₈ : Readability of alarm message	#39 Appearance
DR ₉ : AH operability	#34 Easy of operation

Table 6. TRIZ contradiction matrix of innovative principles of AAR.

Improving parameters	Worsening parameters	
	#32 Adaptability	#48 Measurement accuracy
#45 Complexity	29,28,1,24,15,25,37	28,26,10,2,34,7,37

in raising the alarm. The contradictions in the vessel alarm handling module need to be solved, too. Adaptive and informative alarm messages are necessary for VTSOs to fully understand the current situation. However, information overload may affect “DR₈: Readability of alarm messages” and “DR₉: Alarm Handling (AH) operability”. In total, nine DRs were selected.

4.3. Phase III: Using TRIZ to resolve contradictions identified from QFD.

4.3.1. *Selected DRs classification.* To identify the problem of the current vessel traffic alarm system, the selected DR_j (j = 1 to 9) are classified based on the three modules. Table 4 presents the classification of the selected DR_j.

4.3.2. *The corresponding engineering parameters.* We summarised the relevant engineering parameters for the selected DR_j (j = 1 to 9), as shown in Table 5. The DRs with high priorities are considered as improving parameters and the DRs which contradict them are regarded as worsening parameters.

4.3.3. *Generation of solutions.* The TRIZ contradiction matrices were established based on the DRs classification and relevant TRIZ parameters. Tables 6 to 8 show these contradiction matrices of the three modules. In general, the principles with high frequency were selected.

Table 7. TRIZ contradiction matrix of innovative principles of ATA.

Improving parameters	Worsening parameters	
	#14 Speed	#45 Complexity
#32 Adaptability	<u>10,14,35,24,15,28,12,29</u>	<u>6,28,29,31,35,40,17,25</u>
#48 Measurement accuracy	<u>28,13,24,5,32,35,37</u>	<u>3,35,10,27,1,13,28,26</u>

Table 8. TRIZ contradiction matrix of innovative principles of AP.

Improving parameters	Worsening parameters	
	#39 appearance	#34 ease of operation
#11 Amount of information	<u>7,3,32,19,25,17</u>	<u>25,10,17,6,19,13</u>
#32 Adaptability	<u>29,28,2,32,3,7,24</u>	<u>15,24,3,4,28,14,13,26,10</u>

Table 9. TRIZ-based principles of the problem resolution for Automated case-based track assignment module.

TRIZ Principles	Original operational definition	Software Analogy Interpretation	How to achieve these principles	Proposed Module
28 Replacement of mechanical system	Replace a mechanical means with a sensory (optical, acoustic, taste, or olfactory) means.	Add new functions or features that make the alarm system act in an opposite way.	Building case-based reasoning mechanism in the system to search for similar cases that should alarm operators.	Automated case-based track assignment module

The recommended Inventive Principles for the track assignment module are shown in Table 6. In Table 6, No. 28 (Replacement of mechanical system) was chosen and underlined with relatively high frequency. Table 8 shows that the “No. 28” appears twice. While No. 37 (Thermal expansion) was not selected due to no corresponding interpretation in software analogy (Rea, 2001). Hence, the authors adopted principle No. 28. This refers to replacing a mechanical means with a sensory (optical, acoustic, taste or olfactory) means. The operational definition of No. 28 requires no change in software analogy. Thus, we are inspired to improve the current “manual task assignment module” to a new “automated case-based track assignment module” (as seen in Table 9). It is expected that the automatic track assignment system will alleviate the mechanical action of a mouse click.

For the contradictions in the second module, Inventive principles are recommended in Table 7. No. 10 (Prior action), No. 13 (Do it in reverse), No. 28 (Replacement of Mechanical System) and No. 35 (Transformation properties) were selected, as they have higher frequency than other principles. As shown in Table 10, an adaptive multi-parameter alarm generation module was proposed based on these principles to improve the accuracy and aptness of alarms. This module triggers alarms based on multi-parameters and can modify the trigger algorithm based on users’ feedback.

For the contradictions among the third module, Inventive principles are listed in Table 8. Inventive principles No.3 (Local Quality), No.7 (Nesting), No.10 (Prior action), No.13 (Do it in reverse), No.17 (Transition into new dimension), No.19 (Periodic Action), No.24 (Mediator), No.25 (Self-service), No.28 (Replacement of Mechanical System) and No. 32 (Changing the colour) appears at least twice. Hence, they were selected and underlined.

Table 10. TRIZ-based principles of the problem resolution for Adaptive multi-parameter alarm generation module.

TRIZ Principles	Original operational definition	Software Analogy Interpretation	How to achieve these principles	Proposed Module
10 Prior action	Perform, before necessary, a required change of an object (either fully or partially). Carry out all or part of the required action in advance.	System can provide automatic and adaptive required information in advance.	Using signal selector to reduce repeat alarms.	Adaptive multi-parameter alarm generation module
13 Do it in reverse	Invert the actions used to solve a problem (e.g., instead of cooling an object, heat it).	Think about a function from an opposite viewpoint.	Building reinforcement learning system to modify alarm trigger algorithm based on human performance.	
28 Replacement of mechanical system	Replace a mechanical means with a sensory (optical, acoustic, taste, or olfactory) means.	Add new functions or features that make the alarm system act in an opposite way.	Applying neural network replaces simple threshold to generate alarms.	
35 Parameter changes	Change the degree of flexibility.	Change how the physical service is delivered.	Using multiple parameters Adaptive alarm thresholds to trigger alarms.	

Table 11 shows the operational definitions and software analogy of all these principles. Furthermore, the innovative solutions based on these principles are also presented and discussed in Table 11. To integrate these solutions, an adaptive multimodal alarm presentation module was proposed. It is expected that users can interact with an adaptive multimodal alarm presentation module to identify alarms quickly.

In conclusion, we proposed a module of a smart vessel alarm system with three sub-modules (Table 12), namely (1) Automated Case-based track assignment, (2) Adaptive multi-parameter alarm generation, and (3) Adaptive multimodal alarm presentation.

With a design logic of PQT, we finally conceptualised the system specification to reduce operators’ workload and to improve operators’ situational awareness. The coherence of phase I to phase III of PQT framework for this case study can be found in Figure 7.

4.4. *Final design result: Smart Vessel Alarm System.* The new system consists of three intelligent modules as mentioned above. The functions and advantages are discussed below:

(1) By the use of an automated case-based track assignment module, URs of safety and ease of operation are achieved.

First, to reduce human errors in setting track assignment, we suggested replacing manual assignment with an automated assignment module. Also, the risk levels of entering vessels are screened automatically based on historical data. This module, which implements

Table 11. TRIZ-based principles of the problem resolution for Adaptive multimodal alarm presentation module.

TRIZ Principles	Original operational definition	Software Analogy Interpretation	How to achieve these principles	Proposed Module
3 Local Quality	Change a technical system's structure from uniform (homogenous) to non-uniform; change an external environment (or external influence) from uniform to non-uniform. Make each part of a technical system fulfill a different and useful function.	Change an object's classification in a technical system from a homogenous hierarchy to a heterogeneous hierarchy.	Customising colour, font, size of alarm presentation.	Adaptive multimodal alarm presentation module
7 Nesting	Place one object into another; place each object, in turn, inside the other.	Inherit functionality of other objects by "nesting" their respective classes inside a base class.	Combining related alarms together.	
10 Prior action	Perform, before necessary, a required change of an object (either fully or partially). Carry out all or part of the required action in advance.	Same as operational definition.	Combining alarms before presenting them.	
13 Do it in reverse	Invert the actions used to solve a problem (e.g., instead of cooling an object, heat it).	Think about a function from an opposite viewpoint.	Modifying alarm presentation based on human performance.	
17 Transition into new dimension	Difficulties involved in moving or relocating an object along a line are removed if the object acquires the ability to move in two dimensions (along a plane). Accordingly, problems connected with movement or relocation of an object on one plane is removed by switching to a three-dimensional space.	Use a multi-layered assembly of class objects instead of a single layer.	Utilising multimodal interface to present alarms.	

(continued)

Table 11. Continued

TRIZ Principles	Original operational definition	Software Analogy Interpretation	How to achieve these principles	Proposed Module
19 Periodic Action	Instead of continuous action, use periodic or pulsating actions.	Instead of performing a task continually, determine the time boundaries and perform that task periodically.	Modifying alarm presentation periodically.	
24 Mediator	Use an intermediary carrier article or intermediary process.	Use a mediator to provide a view of data to a process in the context of the process application space.	Adding a mediator to combine alarms.	
25 Self-service	Make an object serve itself by performing auxiliary helpful functions.	Increase operator participation in the delivery of the function.	Operators can shelve alarms.	
28 Replacement of mechanical system	Replace a mechanical means with a sensory (optical, acoustic, taste, or olfactory) means.	Same as operational definition.	Utilising multimodal interface to present alarms.	
32 Change the colour	Change the colour of an object or its external environment.	A colour change function in a photo or drawing program.	Customising colour of user interface to be user friendly	

Table 12. New Adaptive alarm system of VTS: Smart Vessel Alarm System.

Modules	Main Functions	Sub Functions
Automated case-based track assignment module	Vessel information integration	Vessel movement report
Adaptive multi-parameter alarm generation module	Vessel alarm recommendation	Vessel details
	Adaptive alter option	Historical case data, decision tree Audio and/or visual alert
Adaptive multimodal alarm presentation module	Reinforcement learning algorithm	Adaptive range based on human performance
	Adaptive colour scheme	Day/Dusk/Night
	Alarm list	Customised and adaptive scheme, multimodal alarm presentation
	Shelve alarms Alarm evaluation	Unnecessary alarms can be shelved Operators can evaluate alarms to provide foundation of alarm generation

Figure 7. Coherence and results of each PQT phase in this case.

a Case-Based Reasoning (CBR) mechanism, can set track assignment systematically with a self-learning feature. In this way, the VTS operators can supervise the automated track

Figure 8. Comparison of original alarm generation module and the proposed module.

assignment instead of manually setting track assignment. Thus, human errors and their workload could be reduced.

(2) Adaptive multi-parameter alarm generation module can provide alarms that are more accurate.

To reduce floods of false and nuisance alarms and meet URs of accurate alarms, a signal selector and a multi-parameter alarm trigger algorithm are implemented in the new module. The signal selector can be utilised to filter repeat signals. The multi-parameter algorithm is expected to provide correct and valid alarms under dynamic and complex vessel traffic conditions. Moreover, the alarm trigger algorithm can be modified by users' performance. For example, nuisance alarms often ignored by users are suppressed by reinforcement learning mechanisms. Thus, more accurate and suitable alarms can be provided. The comparison of the original and new alarm generation system module is shown in Figure 8.

(3) Adaptive multimodal alarm presentation module can assist operators to detect alarms.

This design solves the problem in detecting alarms. Multimodal alarms which involve sound, visual and haptic alarms are presented to gain operators' attention. Compared with traditional visual and audible alarms, haptic alarms have several advantages. First, haptic alarms can be detected even in noisy environments. Second, haptic alarms offer a particularly effective means of presenting directional signals to operators. Besides alarms with multimodal presentations, an adaptive function is also implemented. Alarm presentation

Figure 9. Comparison of original alarm presentation module and the proposed module.

style is adapted to the operators' preference. Operators can select their background theme, then alarm presentation will adapt to the selected theme. Moreover, a mediator which combines related alarms can be implemented to reduce the number of presented alarms. A comparison of the original and new alarm presentation system module is shown in Figure 9.

5. CONCLUSION. A framework of PQT based on operational processes, QFD and TRIZ is proposed for the purpose of solving the problems of reducing operators' workload and improving operators' situational awareness so as to reduce alarm fatigue. PQT provides a novel integrating approach of TRIZ, QFD and software quality characteristics for designing a new VAS. The novelty and advantages are summarised below:

- Compared with traditional alarm system design process, opinions of users are taken into consideration in a systematic way.
- A process-based method was proposed to guide interviewers to recall URs of alarm systems. The method guides designers to identify URs and provides a foundation for evaluating solutions.

- The inherent contradictions of DRs are eliminated by adopting TRIZ. Moreover, TRIZ principles are applied with software quality characteristics to generate system design inspirations.
- The PQT framework builds a design method for the vessel traffic service area. It provides action-oriented guidance for problems, URs and DRs and innovative principles to solutions.

This work has opened the door to a design of an alarm system based on URs. A current VAS has been analysed. A proposed smart vessel alarm system is also depicted and compared with the current system. This study has advanced user-oriented design for VTS systems.

The limitations of this research are as follows. The relative importance of URs was obtained by expert interview, so vagueness in verbal assessments is unavoidable. In the future, some other knowledge or requirements acquisition techniques, such as laddering, may be applied to elicit URs.

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ETHICAL STANDARDS

This project was approved by the Institutional Review Board of Nanyang Technological University under the Ethics Reference Number IRB-2018-04-007.

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APPENDIX: INITIAL UR CODES

No	Initial UR codes	No	Initial UR codes
1	less false alarms	14	easy to detect
2	less missed alarms	15	Short system response times
3	less repeat alarms	16	noise is not greater than 74db
4	less alarms per minute	17	no need recall
5	less noises	18	Sound bigger under fatigue
6	fewer colours to dazzle the eyes	19	different alarm time for different vessels
7	colour matches with background	20	different alarm time for different speed
8	good shape of alarm message	21	easy to learn
9	no need of manual assign alarms	22	easy to understand alarm message
10	be silent during normal situation	23	easy to select high priority alarms
11	operators can make minor errors	24	easy to respond to alarms
12	less annoying audible alarms	25	less unrelated information
13	less high priority alarms	26	more time to deal with alarms
		27	more information to understand alarms