Theoretical Issues in Ergonomics Science

All at Sea with User Interfaces: From Evolutionary to Ecological Design for Submarine Combat Systems

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Abstract

The quickening pace of technological advancement will require submarine command teams of the future to process greater volumes of data, potentially with fewer operators. User Interfaces (UIs) have evolved to meet current requirements, but this iterative process has propagated legacy design paradigms that may be unsuitable for future system specifications. To understand where improvements may be made, a review of current submarine control room operation is presented, using a sociotechnical systems approach. The social (command team: work, structure, and communication) and technical (combat systems) components are presented for context. An emphasis is placed on Sonar and Target Motion Analysis due to their prevalence within the control room. It was found that current UIs place increased cognitive requirements on operators due to the complexity and quantity of information presented. It is proposed that adopting an Ecological Interface Design (EID) approach could reduce such issues, facilitating effective resource allocation to manage increased data volumes. EID has been demonstrated to be effective across many domains, however, its exploitation in submarine control rooms is limited. Advances in modern submarine combat systems have promoted greater flexibility, providing an opportunity to utilise contemporary design philosophies for designing intuitive interfaces to maintain effective control room performance.

Keywords: Submarine Control Room, User Interface, Ecological Interface Design, Sonar, Target Motion Analysis

Word count: 8, 802

Relevance to Human Factors/Ergonomics Theory

The submarine control room is a complex sociotechnical system, formed of a highly trained command team and advanced combat system, with the objective of successfully completing missions in challenging environments, such as littoral waters (Roberts, Stanton, and Fay 2018). The system has evolved over time and so are highly evolved regarding operational capabilities, but this does not preclude further improvement. Technological advancements are frequently implemented without formal assessment of their impact from a sociotechnical perspective (Roberts and Stanton 2018). On submarine platforms, technological advancements are affording greater capabilities to meet changing requirements of operation (Bateman, 2011, Dominguez, Long, Miller, & Wiggins, 2006). These include new sensors and upgrades to existing sensors, producing larger volumes of data (Stillion and Clark 2015) with a drive to reduce crew sizes (Ly, Huf, and Henley 2007; Masakowski 2000). A critical question is whether such advances are being implemented with adequate consideration of the capacities of the operators, who already process large volumes of information. Of interest for potential improvements are the User Interfaces (UIs), which despite being highly advanced, have design shortcomings that limit operator performance, and the capacity of the entire control room. It is proposed that these issues could be addressed by switching from an evolutionary design paradigm to EID. Such a paradigm shift could allow future control rooms to meet future challenges and maintain effective operation.

Introduction

Submarine control rooms are nerve centres, utilising trained operators and advanced technology to understand the environment and how operational or strategic goals should be met (Stanton and Bessell 2014; Stanton and Roberts 2017; Hautamaki, Bagnall, and Small 2005; Stanton, Roberts, and Fay 2017). A comprehensive understanding of the environment is important for all submarine operations, from both a safety (sea depth, commercial vessels) and tactical (covertness, achieving objectives) perspective. Their capabilities are highly advanced, having progressed over several decades, but this does not mean improvements cannot be made (Stanton 2014).

As the operational requirements of submarines continue to evolve so do the technologies utilised to support safe operation (Bateman, 2011). Submarine platforms of the future will employ new sensors with improved capabilities (Duryea, Lindstrom, and Sayegh 2008; Roberts, Stanton, and Fay 2015), processing larger volumes of data (Stillion and Clark 2015), likely utilising a greater number of displays (Chalmers, Easter, and Potter 2000). However, an increase in the volume of data presented to an operator may not be matched by their capacity to interpret the data effectively (Woods, Patterson, and Roth 2002). Particularly if such information is not represented efficiently, relevant to the operational context (McIlroy and Stanton 2014). Simultaneously, there is a drive to reduce crew sizes (Ly, Huf, and Henley 2007; Masakowski 2000), which could further increase the amount of data each operator has to process, and reduce operator workload (Henley, Schmitt, and Huf 2013; Carrigan 2009).

New User Interface (UI) designs could contribute to achieving these goals without overloading operators, potentially improving control room effectiveness and safety. Evidence of potential benefits have been observed in other domain control rooms, such as petrochemical production (Jamieson 2007) and nuclear power plants (Burns et al. 2008). A sociotechnical system is defined as the interaction of multiple operators utilising technology for completion of purposeful goal directed behaviours (Walker et al. 2008). A submarine control rooms is an excellent example of a sociotechnical system, with multiple operators interacting as a team, utilising a variety of sensors to generate knowledge of the environment to safely complete mission objectives (Ly, Huf, and Henley 2007; Stanton and Bessell 2014; Stanton 2014). The social aspects of the system are formed of the command team and its structure, while the technical systems are formed of sensor, information, and control technology that make up the combat system. As each subsystem contributes to overall system goals, a poorly performing subsystem could reduce the entire control rooms' effectiveness (Meshkati 1991). This includes UIs, which can be critical to success as they facilitate interaction between the human and technological aspects of the system (Walker et al. 2010).

In several submarine accidents, a UI or associated process has been identified as a significant causal factor. For example, the National Transportation Safety Board (2001) (NTSB) investigation into the USS Greeneville highlighted the lack of a working Analogue-Video Signal Display Unit (AVDSU) as a critical failure which resulted in a submarine colliding with a surface vessel. The purpose of the AVDSU unit was to provide repeated SOund NAvigation and Ranging (Sonar; Bj (2011)) sensor data to operators in the control room, and its failure reduced the availability of sonar data. This contributed to the USS Greeneville being unaware of the fishing vessel Ehime Maru, causing catastrophic damage as it surfaced underneath.

Similarly, the Marine Accident Investigation Branch (2016) (MAIB) identified an incorrect classification of the fishing vessel Karen as a causal factor in an incident involving a Royal Navy submarine. This wrong classification meant that the submarine operated close enough to Karen to cause damage to her trawling nets and associated equipment on board. Sonar operators had inappropriately classified Karen as a merchant vessel after analysis. Subsequently, it was assessed to be further away than it was. This led to a loss of separation between the two vessels, during which time the submarine briefly interacted with in Karens' fishing nets. The accident report stated that whilst all systems were functioning properly, the command team (including sonar) were cognitively overloaded and did not have sufficient time to assess contacts, and as such a potential opportunity to reassess Karens' distance, avoiding the incident, was missed

(Marine Accident Investigation Branch 2016).

These incidents demonstrated that UIs are critical components of the control room system and their impact on safe operations and mission outcomes is not just theoretical; despite decades of evolution to successfully meet the demands of today’s maritime environment, they highlight ongoing challenges and the need ensure these are met on a continuous basis to maintain effective control room performance. Specifically, these incidents highlighted potential shortfalls in Sonar and Target Motion Analysis (TMA) UIs, demonstrating that control room capacity could be maximised via the development of UIs that reduce operator workload when gaining an understanding of and operating in complex environments.

The importance of Sonar and TMA is further evidenced by the communications related to each forming a significant proportion of a command teams’ activities (Stanton and Roberts 2017). As integral components of the submarine control room, the interfaces for these roles have been iteratively improved over time to meet the requirements of modern submarine operation, such as increased frequency of operating in littoral waters (Schank et al. 2011). While successful in providing adequate functionality, it is argued that a redesign of these interfaces, instead of evolution from previous interface designs, could offer improved usability by capitalising on contemporary design paradigms (Hall 2012).

To understand how such interfaces could be improved, it is also important to understand the operational context in which they are utilised. As Sonar and TMA are part of the wider control room sociotechnical system their operation is affected by, and affects, the control room. The first section of this paper will detail broader control room operation, and the command teams’ work. The second section will discuss potential shortcomings with current UI designs, and offer Ecological Interface Design (EID) as a paradigm that could optimise the next generation of UIs

The Control Room

A submarine control room is the predominant location for command and control (C2) onboard a submarine. It houses the duty command team and control (sensor and systems) technology, which work in tandem to ensure mission success, whilst maintaining safety and covertness. Control rooms are typically located amidships (centre-ship), directly underneath the conning tower. This placement is a requirement of hull penetrating periscopes, which impose physical restrictions on a control rooms' location (Duryea, Lindstrom, and Sayegh 2008). As the periscope is a solid tube that breaches the hull, a control room has to be directly underneath, as with the USS Nautilus (Ven 1956). Newer submarines use optronics masts, which transfer image data via fibre optic links, and as such do not require hull penetration (Hamburger, Miskimens, and Truver 2011). Consequently, a control room could potentially be located anywhere on the submarine.

Hamburger et al. (2011) noted that a control room relocation appeared to improve Situation awareness (SA) and communications in Virginia class submarines by allowing all watch-standers to occupy the same space. This could potentially be a result of communication bottlenecks being removed, identified by Roberts and Stanton (2018), resulting in operators being able to share information quicker and more frequently. At the level of the individual, SA is defined as 'the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future' (Endsley 1995). However, such a definition does not appreciate the complexity of control room environments. In such environments SA is not held solely in one operators mind, rather it is distributed across many system agents, both social and technical. It is therefore proposed that the control room has Distributed Situation Awareness (DSA), as each actor contributes to overall awareness (Stanton 2016; Stanton et al. 2017). Stanton et al. (2006) defines DSA as 'activated knowledge for a specific task, at a specific time within a system'. This definition is congruent with control room operations, whereby the knowledge of various agents within the sociotechnical system is continuously shared and represented to achieve mission objectives.

An adapted representation of HMS Drakes' Talisman Trainer is shown in Figure 1. The trainer is split into two rooms, control and sound. All personnel except those related to Sonar are situated in the control room. Sonar personnel are in the sound room to reduce ambient noise as far as possible to aid aural detection. Some modern platforms have combined these rooms, such as the Canadian Victoria Class (Hunter, Hazen, and Randall 2014) or the USS Greenville (National Transportation Safety Board 2001), capitalising on sound cancellation technology in headsets to reduce interference from ambient control room noise (Arrabito, Cooke, and McFadden 2005). The co-location of all operators provides an opportunity for shared information screens that could display relevant information, potentially improving DSA. However, these displays will need to be designed appropriately to ensure each operator can assimilate the information they require, for the completion of individual sub-tasks, which may come from several technologies and operators, for the achievement of higher order team objectives.

The Officer of the Watch (OOW) leads the command team during tactical picture creation and is responsible for making decisions regarding submarine safety based on the teams' collective SA. A contemporary submarine control room has dozens of screens available to the Officer of the Watch (OOW) to make these decisions (see Figure 1 for example); the addition of more screens may negatively impact their SA, as their cognitive capacity may be overwhelmed whilst using these screens (Hamburger, Miskimens, and Truver 2011). This is not limited to the OOW, as operators are expected to utilise multiple screens displaying complex information, SA is highly distributed between human and technology both at the level of the individual and the team. Dominguez et al. (2006) found that data integration from multiple sources was a challenge for commanding officers, adding cognitive workload, and requiring near constant communication with operators. Dominguez et al. (2006) also found that vital information was often not displayed appropriately for processing from a commanding officers vantage point (standing at a distance). Operators could provide this information, however, they may be impeded by the command teams’ complex communication structure, or erroneously disregard information that should be shared (Carrigan 2009). Thus, interface designers must consider their location within the control room, their intended purpose, and current mission type, to facilitate maintenance of DSA and effective decision-making.

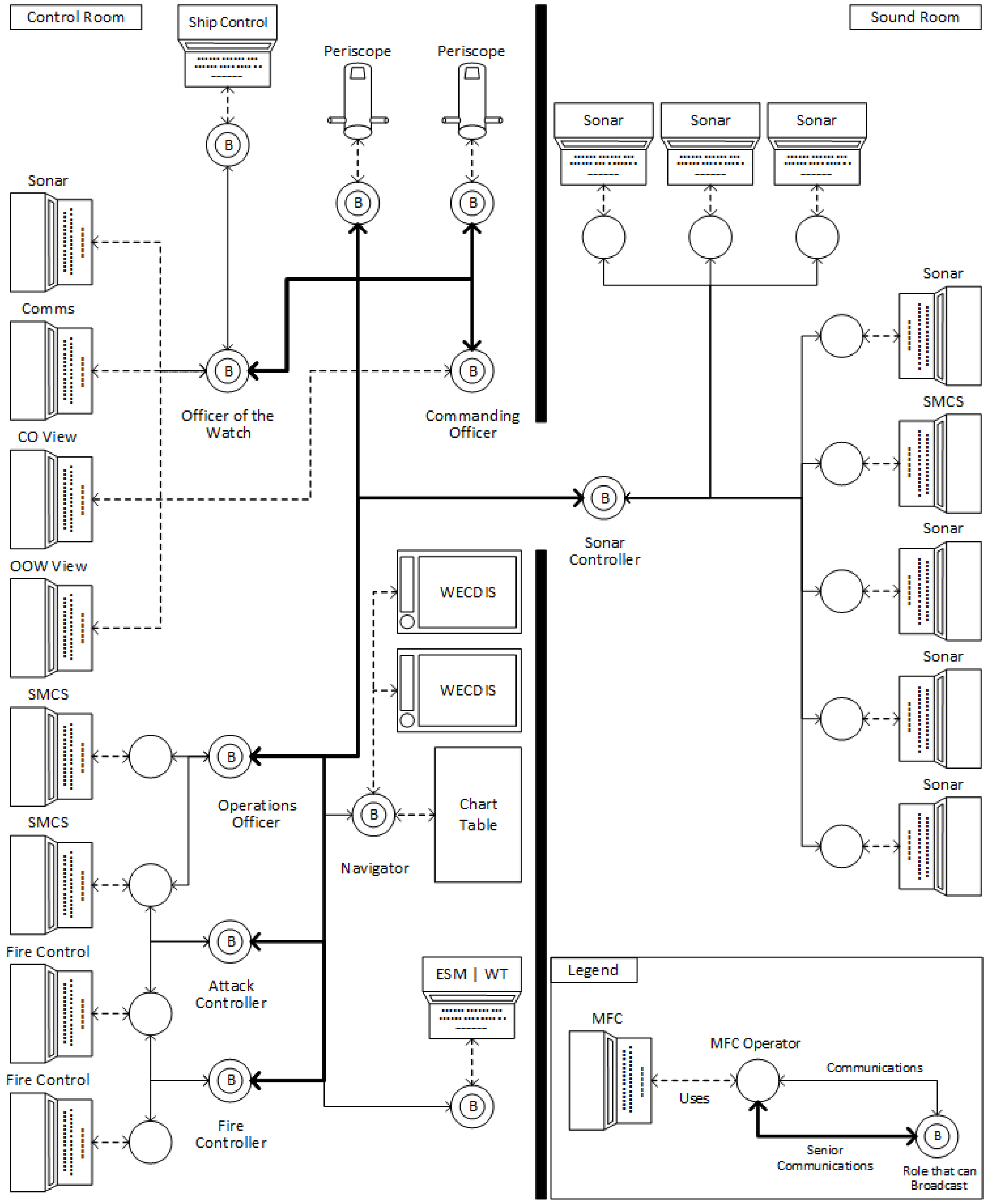

Figure 1 - A typical layout, adapted from Stanton and Bessell (2014), showing both the control and sound rooms. Circles represent personnel that use computer stations (each with multiple screens), dotted lines represent other stations that can be used, thin lines represent communication pathways, bolded lines represent communication pathways for command, and a ‘B’ inside a circle represents that an operator will communicate to all personnel in

the control room. Each console can have multiple screens, each with multiple UIs, to facilitate an operator's job. With so many UIs, it is critical that each performs effectively to ensure optimum command team performance.

Command Team

The control room is operated by a command team, formed of highly trained personnel with different specialisms that contribute towards successful operation. The structure of a command team varies, although typically it is formed of operators and officers, led a senior officer. When creating a tactical picture this will be the OOW, although other officers may lead the control room depending on seniority (e.g.: if the captain is present) and context (e.g.: a specialised activity). An exemplar subsection of the command team structure, that focuses on tactical picture generation, can be found in work by Roberts, Stanton, and Fay (2017). Operators will collect and process information under the guidance of senior operators/officers, who will use the information for strategic as well as tactical decision making (Roberts & Stanton, 2018).

Aims and Objectives

Command teams have three main objectives: remain safe, remain undetected, and complete mission objectives (Mewett 2014; Fay, Stanton, and Roberts 2017; Mack 2003). Remaining safe is considered to be the most important objective (Mack 2003), as the consequences of a poorly maintained tactical picture can have profound consequences, such as the USS Greeneville crash or Royal Navy submarine incident previously discussed (Marine Accident Investigation Branch 2016; National Transportation Safety Board 2001; Drumheller and Benoit 2004). With greater numbers of submarines frequently operating in more complex environments, such as littoral waters (Duryea, Lindstrom, and Sayegh 2008; Bateman 2011), safety must be continuously considered. The team must constantly assess the submarines' position in the water, how this relates to its surroundings, and current threat vulnerability.

Command teams must gain information about their environment to inform possible courses of action, and it is vital that the combat system provides the capability as well as flexibility to support this. Mission objectives are fluid, and can vary, but routine operations typically include tracking vessels, returning to periscope depth, or inshore manoeuvring (Stanton and Roberts 2017); a command team must be proficient in all mission types to ensure safe operations in a contemporary political climate (Bateman 2011).

Work and Communication

The command team works together to continuously update a tactical picture under direction from the OOW (National Transportation Safety Board 2001; Dominguez et al. 2006). A tactical picture is an overview of the submarines' environment, including the perceived positions of contacts. A contact is a vessel or object that has been detected by sensors such as Sonar, radar or periscope, and is being analysed in the control room (Stanton 2014; Wang 2016; Maranda 2008). The tactical picture is used to directly inform operational as well as strategic decisions; therefore, it is imperative to ensure its accuracy (how the environment is perceived vs its actual state). However, the complexity of modern control rooms poses challenges that may negatively affect tactical picture accuracy, namely the volume of sensor data and the communication of this data across the command team via which shared SA is attained (Roberts and Stanton 2018).

As control rooms become more advanced, the amount of data being presented is increasing (Chalmers, Easter, and Potter 2000), this has the potential to exceed an operators capacity to interpret such information effectively (Woods, Patterson, and Roth 2002). This has the potential to negatively impact console operation or verbal communication between which may cause operators to wrongly interpret or process data incorrectly, degrading the accuracy of the tactical picture. In highly demanding situations the cognitive capacities of operators have been demonstrated to reduce in a modality specific fashion, this has the potential to increase attentional focus but also to reduce the volume of information operators can handle (Roberts and Cole 2018). Data is presented to operators on Multi-Function Consoles (MFC), which are computer workspaces (Rhie et al. 2017). Physically, they represent large cabinets, with space cut out to mount multiple monitors, and a shelf for input devices (Bowden and Grosse 2011). Most operators will use a single MFC however, some personnel, such as the OOW, will have access to many different MFCs (Stanton and Bessell 2014; National Transportation Safety Board 2001). Utilising their expertise and MFC, personnel will create and contribute information to the command teams' DSA, which manifests in the overall tactical picture (Stanton 2014). As detailed by Roberts and Stanton (2018), this information is the result cognitive processing being applied to data perceived on an operators MFC. Operators will perceive data, such as a sensor readout, and then gain an understanding through processing the data to create information for the tactical picture. Table 1 provides a list of typically available MFCs within a control room, with sample screens. The OOW views are composites of other MFCs and as such shall not be described.

Table 1 - Description of control room MFC roles, the screens that comprise their functionality, and the overall purpose of each MFC. All MFCs are paired with a communications screen that allows operators to select channels of communication from their headset.

MFC / Role	**Possible Configuration(s)**	**Purpose**
Sonar	Medium Frequency Oscillations (MFO) Towed Array Narrowband (TANB) Flank Broadband (FKBB) Bow Broadband (BBB) Intercept	Detection, Classification, Localisation, and Tracking (DCLT) of contacts
Combat System	Combat System	Generating solutions (bearing, course, range, speed) for contacts to generate tactical picture

Warship Electronic Chart Display and Information System (WECDIS)	WECDIS	Plotting, mapping, navigation
Electronic Support Measures (ESM) Warner Transmissions (WT)	ESM	DCLT and analysis of electromagnetic energy (emitted signals from contacts, communications towers, etc.)
Fire Control	Fire Control	Priming, targeting, controlling, and verifying weapon strikes
Periscope / Optronics	Search Attack	Providing visual DCLT of surface contacts
Ship Control	Helm Controls Plane Controls	Operating ship control surfaces to steer submarine

The complexity of MFCs and the quantity of screens presents a vast amount of data for operators to process. Some control rooms currently provide UIs designed to assist operators in maintaining SA/DSA (Stanton and Bessell 2014; National Transportation Safety Board 2001), such as the AVDSU repeater screen onboard the USS Greeneville. However there may be room for improvement to maximise the utility of these interfaces (Dominguez et al. 2006). For example, Ly, Huf, and Henley (2007) propose that effective watch leader decision making could be supported by interfaces that facilitate information accessibility. Such interfaces are being made possible with modern combat systems, which could represent all information required by operators in one interface (National Research Council 1997), instead of being dispersed across the control room. For example, information from all sensors could be displayed on one screen, removing the need for operators to manually corroborate data about contacts from each sensor manually. This could potentially improve SA/DSA. By implementing changes to simplify the UIs, and the information they display, the potential for overwhelming operators could potentially be avoided.

An increased amount of data also poses communication challenges, such as missed, incorrect, or non-timely communications. Such failures have been recognised as a risk factor in control rooms across many domains (Gibson et al. 2005), including aviation (Cushing 1994) and nuclear (Lee, Ha, and Seong 2011). This challenge of effective communication is further exacerbated by the command rooms' complexity, and the variety of communication modalities, see Figure 1. Information is communicated via a combination of headsets, inter-MFC sharing, loudspeakers, and face-to-face conversations (Stanton and Bessell 2014; Nakashima, Chow, and Wang 2015). Verbal messages received are acknowledged and repeated back, ensuring that the correct information has been received (Murphy 2000b). All communication follows the rank hierarchy, with subsequent levels of leadership aggregating and filtering information until it reaches the OOW (Carrigan 2009). The information is emergent, and generated from interactions between social as well as technical agents, a key trait of DSA (Stanton et al. 2017). Changes to UIs could support more effective control room communication, such as allowing operators to send information digitally to improve speed and reduce the potential for mistakes. In turn, this could mitigate communication related challenges affecting control room operation, potentially reducing the risk presented by communication issues.

Work of Sonar

Sonar is a system for the location and ranging of objects using sound propagation and listening. Its four main functions are Detection, Classification, Localisation and Tracking (DCLT : (Hughes et al. 2010)). To detect a vessel an operator will either hear discreet noise against the oceans background noise, and/or see a concentration of sound on their waterfall forming a line, at a specific Direction of Arrival (DOA), using broadband Sonar, see Figure 2a. Due to advances in modern boats (such as quieter engines, more efficient anechoic tiles, and advanced hull designs) it is possible for some signals from them will be quiet and intermittent, which could result in them not being detected. This is because they may not be readily discernible as clear traces (Matthews et al. 2006). The system does not currently highlight such traces to an operator, which may affect submarine safety if they fail to detect them.

When a vessel is detected, operators assign it an identifier, allowing the system to automatically track and update its location, communicating details to other MFCs such as TMA. This identifier is a tracker (Fillinger et al. 2010). For every time period that a Sonar array returns data, it is plotted as a line on the display. When a new line is added, it moves all others down, giving a waterfall like effect (Asplin and Christensson 1988), see Figure 2d and Figure 2e. Detection, and therefore localisation, is mostly performed using broadband Sonar (Zarnich 1999), which detects sounds within a large frequency range.

Classification of a vessel is typically performed using narrowband (Kendrick and Jmrina 1981), which gives individual frequencies of a signal (Zhiyin and Lin 2009), see Figure 2b. These individual noises are unique and can be compared against databases to identify a vessel. The classification is not validated by the system, meaning that operators are not advised of potentially incorrect classifications, despite the system potentially having the capability to do so. This can affect ownship safety and that of surrounding boats, as demonstrated by the Karen accident.

Tracking of a vessel is performed by analysing broadband trends over time to determine actions a vessel is taking. Speed is also used to track a vessel, which is calculated using a DEMON (Detection Envelope Modulation On Noise (de Moura, de Seixas, and Ramos 2011)/Demodulation of Noise (Mill and Brown 2005)). The calculated speed is passed verbally to be used by TMA. A DEMON waterfall shows a broken down (demodulated) broadband signal, allowing representations of individual shafts and propellers to be viewed (de Moura, de Seixas, and Ramos 2011), see Figure 2c. The frequency of the shaft combined with a Turns per Knot (TPK) value (how many times a propeller turns for one knot of speed) allows speed to be calculated. The TPK is obtained from a classification database or can be estimated based on the type of vessel. As the system does not validate classifications, TPK values can also be wrong, which will invalidate the contacts known position; it may be closer than thought, potentially on a collision course with ownship. The speed, together with the contact cuts, are passed to TMA with the tracker designation.

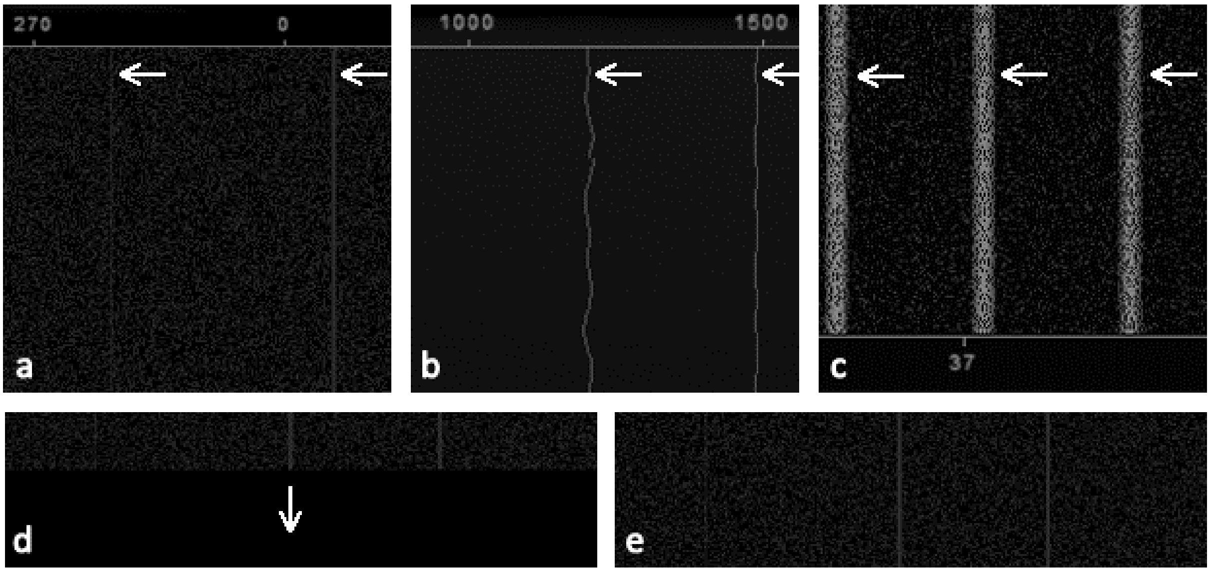

Figure 2 - a) A broadband waterfall showing ambient sound, with two vessels being detected, b) A narrowband waterfall showing the frequencies making up a broadband signal, c) A DEMON waterfall showing the number of propeller shafts and blades detected for a contact. Each group of lines represents one shaft, with the number of lines representing blades, d) A broadband waterfall display that has just started to show data, notice the bottom is empty e) Data at the top of ‘d’ has been pushed to the bottom by newer data, giving a waterfall effect

Work of TMA

TMA is the process of analysing positional data from contacts derived from passive sensors to produce a location, and predicted movements (Murphy 2000c). This is called a ‘solution’, comprising speed, course, range, and bearing of a vessel (Genç 2010). Bearing is the direction to a contact from ownship. To generate solutions, a Local Operations Plot (LOP) can be used (see Figure 3a). A LOP is a chart with a contacts’ previous detections plotted, allowing solutions to be calculated (Clarke 1999).

When a sensor such as Sonar makes a detection, a ‘cut’ will be sent through from the detecting MFC to TMA (Stanton and Roberts 2017). A cut is a straight line that represents the Line of Bearing (LOB) for a signal; it is plotted on the LOP between the submarines position and the maximum detection range of a sensor, with an angle equivalent to the detection bearing. Cuts from each sensor are grouped by detected vessel, with one shown at a time. Operators can merge cuts from two sensors and treat them as one contact (Huf, Arulampalam, and Manning 2006), which provides more information on its behaviour. However, if the system does not verify merges, it is possible for operators to perform a merge using two (or more) discrete contacts, which will result in incongruent information from multiple sources being displayed to an operator, potentially negatively affecting SA/DSA.

Once enough cuts have been accrued for a vessel, an operator can start analysing the vessel’s path using a speed strip. A speed strip is a manoeuvrable visualisation of a vessel’s historic path in the water (DeAngelis and Green 1992), with optional marks to represent where a vessel would be if the path was correct. Whilst the strip is manoeuvrable, it can be cumbersome for operators to move to a desired solution position. A mark is added onto the strip for each cut. The strip is aligned over the cuts by an operator, and if the marks intersect the cuts, the vessel *could* have travelled in the manner indicated. An accuracy measurement view represents the spatial difference between cuts and speed strip, with dots representing the strips’ intervals. As a solution becomes more accurate, the dots will form a vertical ‘stack’, showing they are close to the cuts they represent and align with each other (Huf, Arulampalam, and Manning 2006). The term ‘*could*’ is used because there are multiple speed strip configurations that may align, however they would not all be correct (DeAngelis and Green 1992).

Whilst the system provides a method to validate the accuracy of a solution, it does not assist the operator in creating an accurate solution. For example, there is no option to fix cut marks to their matching cuts, significantly reducing the number of available solutions. Figure 3c-e shows sample LOPs, demonstrating how the speed strip matches cuts in a variety of configurations. Once a solution that matches all cuts is derived, see Figure 3b, it is shared (Huf, Arulampalam, and Manning 2006). Sharing is where contact information is made available to other nodes within the system. When this occurs, it is plotted as a contact marker onto the geographical view, see Figure 4b, allowing relevant personnel to view the vessels location. On some systems a contact marker already exists, but it is marked with a cut to indicate that only bearing is known, see Figure 4a. Unless a vessel changes its parameters (how it is moving) or the accuracy degrades, the solution does not need to be manually updated, dead reckoning will be used to plot further movements. Dead-reckoning is plotting positional data by extrapolating previous trends (Murphy 2000a). For example, if a solution had a vessel travelling at ten knots, the contact marker would move as if travelling at that speed without needing operator intervention, illustrated by contact markers moving between Figure 4b and Figure 4c.

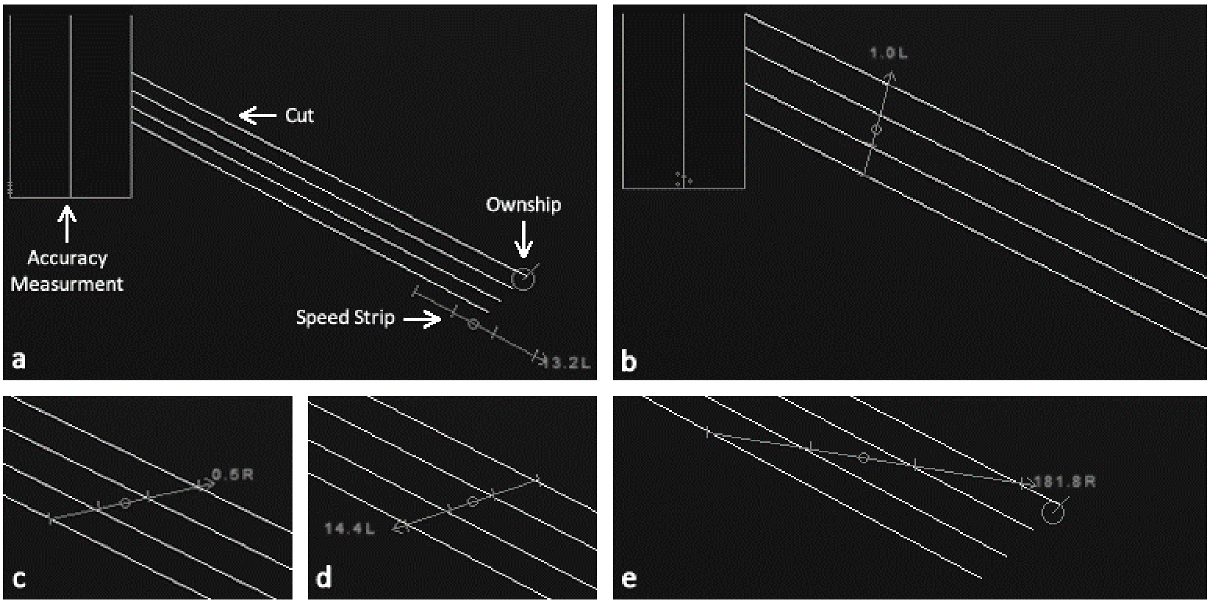

Figure 3 - a) A Local Operations Plot interface screenshot, with different aspects labelled, b) A finished solution, ready to be shared. Notice how the dots in the accuracy measurement have gotten closer to the centre line, representing how the ruler notches correlate with the cuts, c) d) e) Different solutions that match, demonstrating that using just cuts can yield incorrect solutions

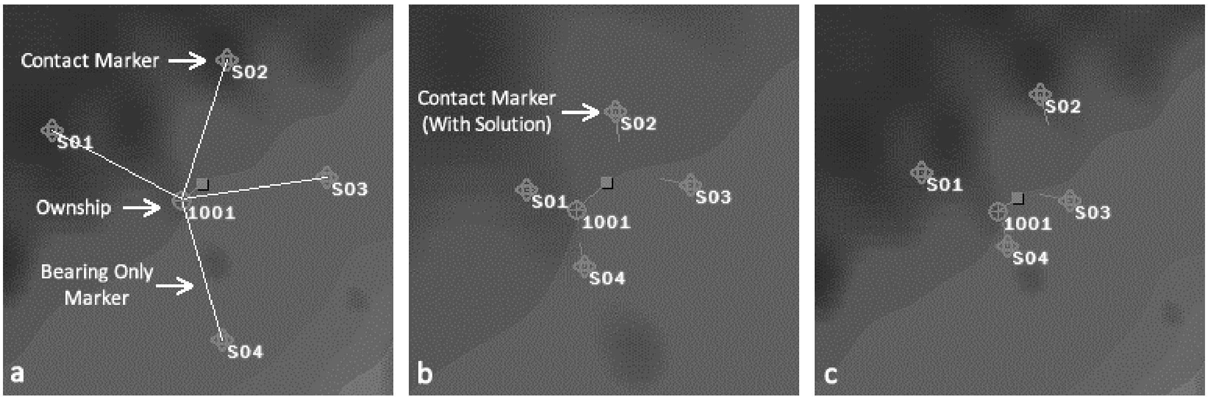

Figure 4 - a) A geographical view with four contacts marked when only their bearing is known, b) A geographical view with four contacts marked with full solution data, c) Illustration of automatic movement of contacts from ‘b’ over time

Combat System

The activities of the command team are supported by the combat system, which encompasses a wide variety of technology available within the control room. A combat system comprises multiple software subsystems including Sonar, periscope, radar, and command systems such as the Submarine Command System (SMCS : (Dominguez et al. 2006)). Combat systems facilitate management of information about contacts and make such information available to the command team. Systems are partially networked, facilitating data sharing between the Sonar and control room (Emery 2010; Owen et al. 2006). Each software subsystem could also be considered a technical agent in the control room sociotechnical system, as they engage in goal directed behaviour (providing sonar data, tracking targets), and interact with other agents, both socio (displaying and receiving information) and technical (networked communication). This provides further evidence of control room DSA (Stanton 2016), with technological agents also sharing information to facilitate maintenance of SA.

Backend - Open and COTS Systems

Typically, combat systems have been created to bespoke military specifications (MILSPEC), with subsystems supplied by different vendor(s). However, defence agencies are now adopting Consumer Off the Shelf (COTS) systems to create open architectures, such as the Royal Navy (Owen et al. 2006) or the United States Navy (Womble et al. 2011). Common Core Combat System (CCCS) is the Royal Navy's' COTS based combat system, and was created to lower lifetime costs, support reusability, modularity, and capability progression (Owen et al. 2006). Information sharing is no longer restricted to pre-programmed communications between systems, defined in a MILSPEC, rather all information is available and systems can subscribe to receive what they require (Owen et al. 2006). For example, as soon a sonar speed is calculated, it could be shown on all TMA screens. This could address the communication bottlenecks identified by Roberts and Stanton (2018), removing the need for multiple sociotechnical agents to be involved with the transfer of data via verbal communication. Furthermore, it may also make the attainment of DSA more efficient by allowing MFCs, which can communicate almost instantly, to share information at a faster rate than what is encountered when information is verbally passed between multiple command team operators.

A cluster of COTS servers are used to create a Shared Computing Environment (SCE), which powers all control room technology, including legacy systems. Using a COTS cluster has resulted in increased processing power and a reduced footprint in comparison to previous systems. For example, onboard HMS Astute, Sonar 2076, command, and navigation functionality are now powered using sixteen processor parts, instead of over 200, housed in only a few cabinets (Defence Equipment and Support 2010). This has created the physical space and computing capability for the addition of more systems that could assist operators, such as artificial intelligence agents to solve complex TMA datasets. Additionally, newer capabilities allow deployment of updated UIs, such as the new Sonar 2076 update designed to capitalise on cutting edge sonar technology (Royal Navy 2015).

The benefits of adopting a new generation of combat systems are clear, driving futuristic capability with consideration for organisational factors, such as cost and risk. It is imperative however, that UIs are developed at the same pace to make full use of the systems.

Frontend - User Interfaces

Adoption of open combat systems has included the upgrade of MFCs, changing UIs to improve functionality and usability. In doing so, two key problems are addressed: the stasis of core UI concepts and the addition of new features.

Despite considerable capability advances across the history of submarines, certain UI aspects have remained the same. This is illustrated in Figure 5, a collection of Sonar UI images ranging from 1989 to 2015. Leftmost is from the USS Hyman G. Rickover (SSN-709) and rightmost is Sonar 2076, used across the Royal Navy's' contemporary submarine flotilla. Exact dates and implementations are classified, however little difference is apparent. Whilst specifics such as screen layouts or different waterfall aesthetics, have changed, large commonalities remain (such as the use of green and black, or the 'waterfall' display: new data moves old data down the screen, causing a waterfall like effect).

Each interface, a product of their time, met requirements within the available budget, computing capabilities, and core considerations for submarine design (Burcher and Rydill

1995). As time progressed, budget sizes (Fallon 2015) and computing processing power increased, allowing more processing to be achieved, but the previous interface style tends to have been retained. This has resulted in highly advanced systems, but ones that employ legacy design paradigms. Reasons for this could be the retention of existing training programmes, SME familiarity with existing systems, or the potentially risk associated with 'buy-in' to next generation UI (Hall 2012; Gosling 2008).

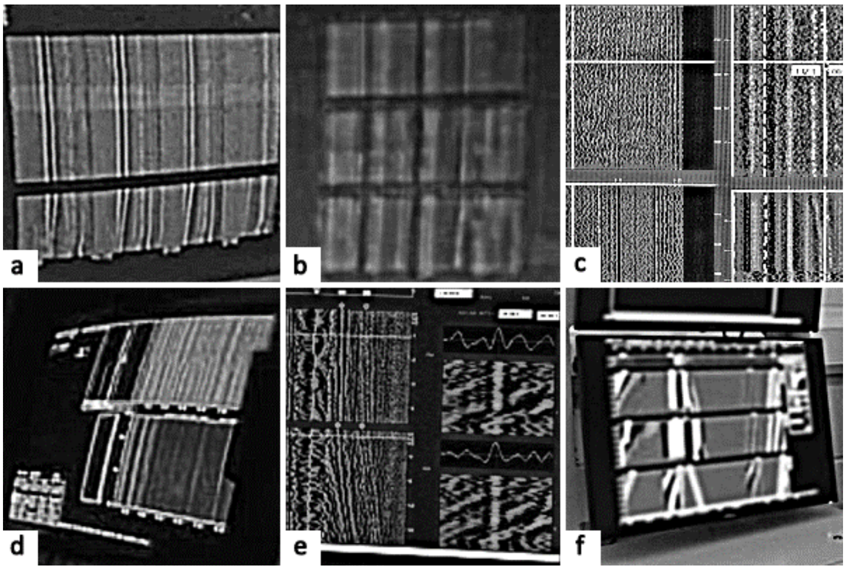

Figure 5 - Chronological screenshots of Sonar user interfaces. While spanning three decades, the waterfall from 1989 is visible on each. a. Hoffman (1989), b. Bosner and Oxley (2009), c. Jones (2009), d. Canadian Armed Forces (2013), e. Webber (2015), f. Royal Navy (2015)

Additionally, onboard factors such as space requirements for supporting equipment, processing power, system compatibility, and implementation time may have led to UI development occurring at the same pace as wider system changes (Defence Equipment and Support 2010). Nevertheless, submarines are at the forefront of technological innovation. For example, Sonar 2076, while having a similar UI to predecessors, is vastly more capable, with increased detection capabilities (Royal Navy 2008). While individual changes seem small, their combined effect can be observed comparing the Turtle (Clautice 1978) to HMS Artful (BAE

Systems and Launderdale 2016). HMS Artful, like all submarines in the Royal Navy, is highly advanced, allowing command team personnel to carry out a multitude of deployment objectives. This success has been engineered from continuous improvement of the entire submarine, including user interfaces, such as Sonar 2076, to maximise exploitation of these modern capabilities in an evolutionary fashion (Roberts, Stanton, and Fay 2015).

Future Design Considerations

Current Design Issues

Whilst submarine control rooms are currently an advanced product of evolution, afforded by constantly trained operators and ever changing combat systems, it does not mean they cannot be improved upon (Stanton 2014). In particular, the lack of substantial UI development, discussed above is an area that has the potential to maximise current and future capabilities. The challenges of a contemporary and future global maritime environment may necessitate changes to remain at the vanguard of capability as well as safety. As a complex sociotechnical system, there are a variety of aspects that could be assessed to see where changes could be implemented, such as crewing requirements or sensor capability. However, the USS Greeneville and Royal Navy submarine incidents have highlighted that UIs can play a critical role in control room operation, performance, and safety, creating an impetus to assess how they may be improved to avoid future incidents and to capitalise on new advances and capabilities provided by modern combat systems.

Maintaining a tactical picture relies on operators understanding and creating information about their environment. Despite this, information from UIs often takes on a different form, unrepresentative of its physical manifestation, requiring it to be perceived and processed. For example, despite representing 360° of aural signal, the Sonar waterfall is not circular, requiring operators to translate the plot of their surroundings. For TMA, details about a cut strength are not represented, and the last cut is not marked. Furthermore, design issues such as transient signals in the sonar waterfall not being highlighted, or TMA solutions not being constrained may add further complexity and cognitive workload. Interactions between perceptual and cognitive processes can affect operator performance (Hanisch, Kramer, and Hulin 1991; Masakowski and Hardinge 2000), as can overly complex screens (Coll and Wingertsman 1990). As most control room tasks focused on a submarines' immediate environment, especially with Sonar and TMA, the EID paradigm could offer a novel approach for future development.

Ecological Interface Design

EID is a theoretical framework for designing Human Machine Interfaces (HMIs) of a complex nature (Vicente and Rasmussen 1992), making the affordances and constraints of a system and its environment apparent to operators (Van Dam 2014). The framework is based on Abstraction Hierarchies (Vicente 1999; Jenkins et al. 2009) and Rasmussens' Skills Rules Knowledge (SRK) Taxonomy (Rasmussen 1983). It has two objectives, not forcing cognitive processing to a higher level than tasks require, and supporting all levels of cognitive control described by the SRK Taxonomy (McIlroy and Stanton 2014).

An Abstraction Hierarchy (AH) is the output of Work Domain Analysis (WDA) in Cognitive Work Analysis (CWA). It represents a work domain in five levels of abstraction, from physical objects to reasons for existing, revealing the Physical and Functional requirements of a work domain, thus facilitating an understanding of how it works, and why it exists (Rasmussen 1985; Vicente 1999; Vicente and Rasmussen 1992). Reduction of cognitive demand is achieved by displaying the identified Physical and Functional information in an ecological manner, allowing the interface to take advantage of human perception and psychomotor abilities (Dinadis and Vicente 1996). In an interface, Physical information represents and describes the status of system components, and Functional interface information is representative of system structure and constraints (Pawlak and Vicente 1996). Traditional interfaces only present Physical information, whereas EID also presents Functional information. This can lead to better performance than either alone (Torenvliet, Jamieson, and Vicente 2000; Vicente 2002), which could combat the issue Woods, Patterson, and Roth (2002) identified of increased control room data potentially exceeding an operators capability to effectively process it; operators would be able to process more data, without compromising their ability to do so.

The SRK Taxonomy posits that each taxa is a distinction of behaviour originating in response to fundamentally different representations of environmental constraints (Rasmussen 1983; Vicente 1999). Each SRK taxa correlates to a EID design principle, supporting behaviour based upon it (Vicente and Rasmussen 1992): Skill-Based Behaviour (SBB) requires that an operator should be able to manipulate the interface directly, with objects being isomorphic to what they represent, Rule-Based Behaviour (RBB) requires a consistent one to one relationship between signs and constraints, Knowledge-Based Behaviour (KBB) requires that the work domain is represented as an AH, providing an external mental model to support knowledge based problem solving. Support of different levels of cognitive control is achieved by observing these design principles, facilitating innate response mechanisms (Vicente and Rasmussen 1992), such as recognising red contacts as dangerous, or understanding the environment from looking at the tactical picture.

EID has been shown to improve performance compared to traditional systems (Vicente 2002), increase work domain transparency (Van Dam, Mulder, and Van Paassen 2008), reduce workload (Nielsen, Goodrich, and Ricks 2007), and reduce memory requirements (Lau and Jamieson 2006). Given the synergy between the goal of EID and a submarine command room in understanding environmental constrains, it is posited that the framework would be highly suitable, and could potentially combat issues identified with current UIs, which could have benefits for the entire control room.

Existing Designs

The potential of EID as a design paradigm has already been demonstrated across a variety of domains, including power generation and petrochemical production (McIlroy and Stanton 2014), revealing performance similarly complex control room environments to submarines. The parallels that can be drawn between the issues faced by complex control rooms in other domains and the maritime domain strengthen the case EID to be applied; it would be an egregious oversight to ignore these parallels and the substantial body of literature (McIlroy and Stanton 2014) highlighting the application of EID.

Lau et al. (2008) identified that while conventional Nuclear Power Plant (NPP) interface design had led to interfaces with acceptable performance and safety records, unanticipated events had been a causal factor identified in accident investigations. They noted that unanticipated non-routine events were precursory to these accidents, arising because of the complexity of modern NPP control rooms. To mitigate this, EID interfaces were designed that would aid operators in handling the complexity of modern control room. An assessment of these designs by Burns et al. (2008), showed increased SA in certain circumstances, demonstrating the potential for EID to be successfully applied as a design paradigm in NPP control rooms.

In the petrochemical industry Jamieson (2007) identified a failure of interface technologies to match technological advances as a contributory factor towards an estimated billions of dollars (Bullemer and Nimmo 1994) in annual avoidable losses. They designed and tested EID interfaces for production control and found evidence of potential benefits for application of the paradigm in an industrial setting. It was also noted that these benefits demonstrated that EID should contribute to improving safety and productivity.

In the maritime domain, organisations are making design changes, and consequently systems that encompass some of the principles of EID to varying degrees already exist for Sonar (Atlas Elektronik 2016a) and Combat Management (Havelsan 2015; General Dynamics 2014; Atlas Elektronik 2016b). Research is also being conducted on different design paradigms for future interfaces (Ly, Huf, and Henley 2007; Hunter, Hazen, and Randall 2014; Danczyk et al. 2015). #Whilst these systems may not incorporate all aspects of EID, such as using a WDA, or displaying both Physical and Functional information, they demonstrate that EID principles could be used successfully for Sonar and Combat management, changing aspects of their predecessors that would have incurred cognitive workload penalties associated with perceiving and processing information. It would be pertinent to compare these interfaces in order to understand whether they improve ways of working, compared to current interfaces.

Differing designs already exist within the literature, such as the proposed navigation aiding interfaces by Danczyk et al. (2015) (see Figure 6) and Ly, Huf, and Henley (2007) (see Figure 7). Whilst not performing the same functionality, they have a core set of features they both complete, as would be expected from a navigation system. Both interfaces achieve these features using very different UIs. As interface design can be subjective, the ecological representation of objects may differ, producing differing usability in certain aspects. Thus, while it is important to build upon already successful designs, it is also useful to explore alternative design philosophies.

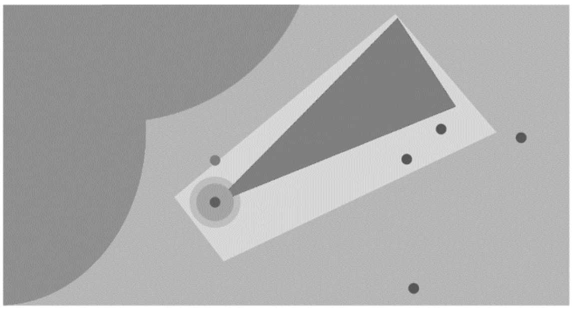

Figure 6 - A simple representation of a navigation assistance interface proposed by Danczyk et al. (2015). All known contacts are plotted on this screen, allowing for better situation awareness and tactical decisions.

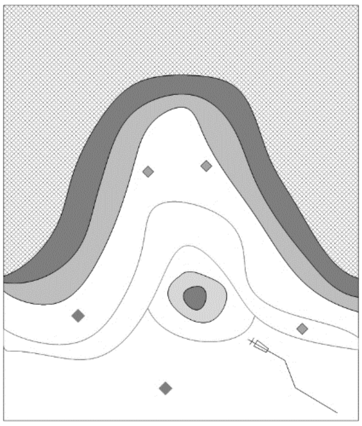

Figure 7 - A simple representation of a navigation assistance interface proposed by Ly, Huf, and Henley (2007). Again, all known contacts are plotted, but using different representations.

Interfaces utilising EID principles are not just limited to research. Warship Electronic Chart Display and Information Systems (WECDIS) are already present in modern submarine control rooms, presenting chart data in an ecological fashion to aid navigation. An example WECDIS interface, adapted from Offshore Systems Ltd (2007), is shown in Figure 8. The ownship icon and land representations are Physical information, showing the current environment. Functional information is overlaid to show areas of danger, calculated from factors such as sea depth, current and geographical features. Whilst some interpretation must still be performed, the environment and its constraints are immediately apparent. This is a core aspect of EID and demonstrates the methods suitability for use in submarine control rooms. Furthermore, it establishes precedence of EID being used by the Royal Navy, showing that it can successfully integrate and provide training on a new generation of interfaces.

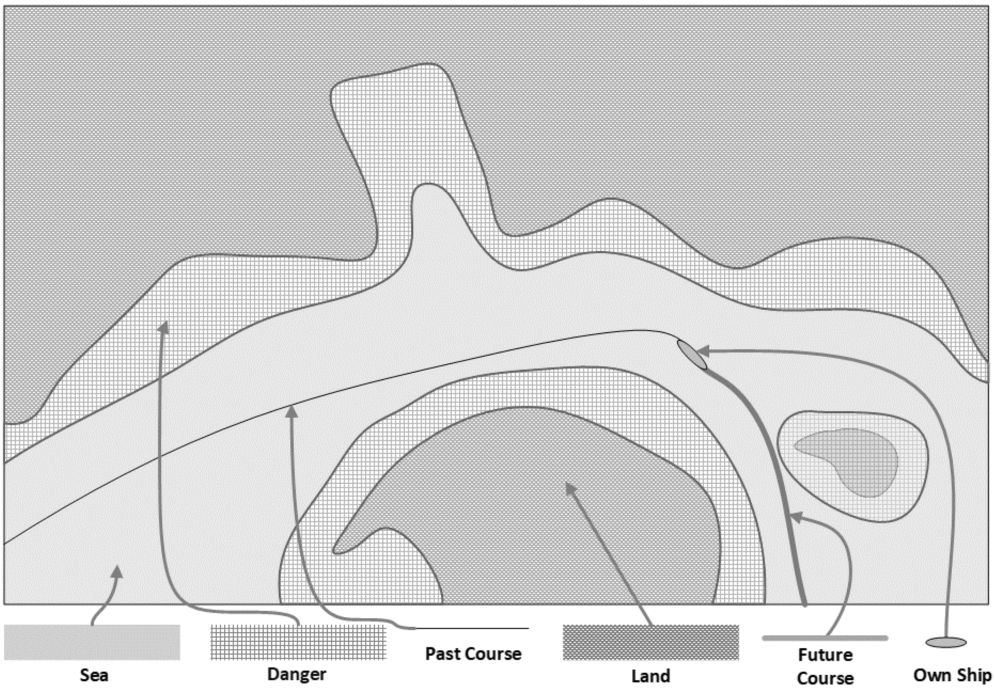

Figure 8 - A simple representation of a WECDIS product, made by Offshore Systems Ltd (2007). Representation of the land provides Physical information, and highlighted areas of anticipated danger provide Functional information. By displaying these areas, an operator will not have to determine their presence manually. The presence of both Physical and Functional information is in accordance with EID principles, demonstrating their application to the maritime domain.

EID Application to Sonar and TMA

A precedence for implementation in an operational submarine control room further strengthens the case for EID. Moreover, it addresses organisational as well as technical factors that may have affected redesign efforts previously, such as a desire to maintain training readiness (Hall 2012), reduce cost as well as risk (Gosling 2008), and technical capability; if these can be overcome for one system there may opportunity for other systems, such as sonar and TMA. The remainder of this section outlines initial ideas of how EID principles could be realised within these systems.

With modern combat systems such as CCCS affording MFCs greater access to data, displaying both Physical and Functional information could be achievable. For example, consider a TMA interface that is showing Physical cut information from sonar. A TMA operator may not be aware of the maximum sonar detection range at a given time and may attempt to place a solution outside of this range. Alternatively, they may attempt to place a contact in the sonar baffles (blind spots), which is improbable, as no cuts would be being received.

In both instances, Functional information regarding the sonar sensors range and coverage could be overlaid onto the LOP to provide the operator with constraints to place the solution inside. Currently, the TMA system does not have this functionality, placing the onus on operators to perform these checks mentally. Whilst operators are well trained, a high workload situation may lead to mistakes or omission of sense checks. Furthermore, whilst sonar information could be retrieved from a sonar operator, bottlenecks in the system may impede effective and timely communication of this data (Roberts and Stanton 2018). Providing support directly in an EID may relieve these issues, by reducing cognitive workload (e.g. mental manipulation of complex material) and additional communications across a complex network. In turn, this would benefit the entire control room sociotechnical system by ensuring accuracy of the tactical picture to ensure ownship safety, the top priority of any submarine (Mack 2003).

For operators working directly with MFCs, such as sonar and TMA, improvements could be made to assist operators overcome challenges in their usage. For example, transient sonar signals are not currently highlighted. Therefore, operators must continuously scan the waterfall history for these signals, or a pattern of signals (Matthews et al. 2006). This adds additional workload and may distract the operator from other tasks. Following an EID approach to sonar design, support for RBB could be added, and transient signals could be highlighted to draw operators' attention for investigation, removing the need for them to manually find these signals.

As sensors become more advanced, they will detect more contacts. Maintaining suitable SA about each of these contacts may exceed an operator's capability unless the UI allows intuitive storage and interpretation of the data. For sonar, this could be achieved by adding support for SBB in the interface, by utilising a skeuomorphic representation of available arrays. Current representations require mental translation to a 360° representation, creating additional operator workload. Representing the waterfall data using a sensors geometry could remove this workload, allowing operators to initiatively understand the location of traces in relation to ownship.

KBB behaviour could be supported by ensuring that operators have all required information available to support their tasks within their UI. This may be of substantial benefit to TMA operators, who incorporate information from a variety of social and technical agents within the control room to generate contact solutions. Whilst modern combat systems are advanced, certain information is still transferred manually, such as the speed calculated by sonar. The speed is generated within a sonar MFC, yet is not passed digitally, nor displayed to a TMA operator. This adds unnecessary communication and relies on the TMA operator to manually incorporate the speed into their solution. Given the amount of data being processed by TMA, this could add a substantial cognitive workload, which may be further exacerbated in the future by more advanced sensor capabilities. An EID design incorporating all required work-domain information could reduce the cognitive workload and difficulties (communication bottlenecks, many screens) associated with collating it manually; when information pertinent to TMA is generated by other MFCs, it could automatically be displayed to TMA operators, and their solutions validated against the information.

In addition to taking advantage of innate abilities, supporting appropriate multi-level control allows operators to behave effectively when faced with new, unfamiliar situations (Drivalou and Marmaras 2009), assisting a correct and safe outcome. With submarines undertaking more missions and mission types than previously, such situations may be encountered with a greater frequency, potentially leading to incidents such as the USS Greeneville (National Transportation Safety Board 2001) or Karen (Marine Accident Investigation Branch 2016) accidents. EID interfaces for operators that rely on summary screens, such as the OOW, could enhance their SA and decision-making process during these situations.

For example, if a close proximity contact on a collision course with ownship were detected suddenly, then the OOW would be required to manoeuvre quickly and correctly to avoid the danger. If diving were not possible due to operating in busy littoral waters, the OOW would have to steer the submarine to a safe area of water. The OOW may be storing the tactical picture in their mind, without any effective assistance from command room screens (Ly, Huf, and Henley 2007); this would require the OOW to calculate a course of action mentally, which may incur a temporal penalty and not be the optimal course of action. Decision support screens, such as those proposed by Ly, Huf, and Henley (2007) and Dominguez et al. (2006), designed using the EID paradigm could address these issues, allowing the OOW to plot a safe course of action with a comparatively low cognitive workload. This functionality could even be extended further to plot optimal courses to safety automatically. As a maritime environment can be challenging and unpredictable, it is advantageous to provide this support, reducing the risk posed from unfamiliar situations.

In summary, whilst evolutionary design has yielded capable control rooms, there are still difficulties associated with their operation. This issue is present across multiple domains, not just maritime. However, EID could provide a means to mitigate these issues, and there is a substantial corpus of evidential literature. With the objective of EID being synergistic with submarine control room operation (understanding the environment), and its core design goals supporting key issues identified across the control room, there is a strong case for it to be adopted as a design paradigm. Furthermore, implementation of EID interfaces may not have been previously possible due to organisational (risk aversion, training requirements) or technical factors (computing capability). However, with the advent of modern combat systems addressing these factors, combined with a precedence of adoption, an opportunity is afforded to capitalise on a design paradigm that could contribute to ensuring suitability of future control rooms for challenges that lie ahead.

Summary & Conclusions

Submarine control rooms are an advanced product of design evolution over several decades, but this does not preclude further improvement. Whilst an evolutionary approach has kept submarines at the vanguard of capability, using contemporary means to achieve their mandate, emergent issues require addressing if they are to be capable of meeting the future demands. Additional sensors, more data, more displays, and reduced crew numbers will create an onus for improvement that must be met to operate effectively. A need to address emergent issues stemming from increasing requirements is not necessarily limited to submarine control rooms. While control rooms across many domains continue to evolve to meet current requirements, future requirements may challenge this model of adaptations' success.

The interactions of the command team and the combat system to achieve a variety of missions defines the control room as a sociotechnical system. One area of improvement may be the UIs, which can be critical factors to success; current designs can accommodate contemporary submarine capabilities, however as the envelope of innovation is pushed, their efficacy is diminishing. This issue is not limited to the maritime domain. Avoidable losses for petrochemical control rooms or accident causation in NPP control rooms, serve as motivation to explore how best to meet future challenges. Decreased effectiveness has led to accidents where a UI was identified as a contributing causal factor. Thus, it is pertinent to assess how they may be improved, initially concentrating on sonar and TMA in the maritime control room domain due to their prevalence.

The command team works to generate a tactical picture, whilst maintaining the three main objectives of submarine operation: remain safe, remain undetected, and complete the mission. As missions can be varied and complex, it is important that UIs support operators in all situations to maintain effective performance. This performance may be negatively affected by the complexity of control room operations and the UI. In the past, organisational and technical factors have impeded implementing a solution. However, modern combat systems could provide an opportunity to make UI design changes. While this paper has concentrated the maritime domain, it is possible that other domains are making advances that could facilitate similar design changes. For all domains, a step change in UI design could ensure optimal operator performance, and that they are fully supported by the interface.

EID is proposed to mitigate issues with current UI design, as the nature of work within the control room is synergistic with what it provides as a design paradigm (McIlroy and Stanton 2014): a focus on the environment, its properties, behaviours, affordances, and constraints. While designs employing EID principles currently exist for both Sonar and Combat Management (which includes TMA), with some in use within fleets, it does not mean that they cannot be improved upon; the benefits, or otherwise, derived from redesigning using EID should be explored to ensure their continued future effectiveness. As with their predecessor interfaces, these EID systems should continue to be evolved to stay at the vanguard, facilitated by the domain specific advances (such as the flexibility and power of open command systems for submarine control rooms). The potential benefits of EID, coupled with the capability to realise them provides an interesting research space across multiple domains, which should fully be explored.

Declaration of Interest Statement

No potential conflict of interest is reported by the authors.

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