

Optimising the design and functionality of submarine control rooms from a sociotechnical systems perspective

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Abstract — The requirements for submarines of the future will be shaped by technological advancements, operational need and economic constraints. This will include additional instruments (e.g. Unmanned Underwater Vehicles), improved sensor capacity (e.g. higher fidelity sonar arrays) and maintenance/reduction of crewing requirements. Future submarine control room teams will therefore, be required to manage and interpret greater volumes of data, with minimal increase to crew size. Advanced technologies are often implemented without formal assessment from a sociotechnical perspective. A series of human-in-the-loop studies were conducted to document contemporary functionality and identify future design concepts. A representative submarine control room simulator was built based upon an ASTUTE class submarine. The analysis used was a new shortened form of Event Analysis for Systemic Teamwork (EAST). EAST models complex collaborative sociotechnical systems through a network approach. Specifically, three networks are considered: task, social, and information. Examination of contemporary ways of working revealed a number of communication bottlenecks between operators in the control room which resulted in a delay of critical information transition across the control room. The network distance between operators dependant on each other for task relevant information was also high, limiting the productivity of the command team. Engineered social loafing was observed, primarily as a result of the communication bottlenecks. Finally, there was a lack of sensor information alignment resulting in disparate information requiring operator intensive decision based integration. The EAST method is a novel way of documenting and quantifying complex sociotechnical systems. It models the functionality of complex sociotechnical systems in a manner accessible to a broad audience. The output of this analysis has the potential to facilitate requirements elicitation for future system upgrades whilst simultaneously forging a common understanding between academic, industry and military partners regarding future aims and requirements.

1 Introduction

A sociotechnical system requires human operators and technology to work together with growing levels of independence to complete goal-directed behaviours for the achievement of successful overall performance [1]. The submarine control room has evolved across many decades of operations and so represents a highly advanced sociotechnical system, but this does not mean that it cannot be improved [2]. In such systems cognitive processes and situation awareness are distributed across many operators and agents in the system, rather than being held in solely in the minds of individuals. Whilst the commanding officer is ultimately responsible for the safety and overall operational performance of the submarine, decision making relies on the effective integration of large volumes of information from disparate sources, both technological and human [3].

The requirements for submarines of the future will be shaped by technological advancements, operational need and economic constraints. Submarine control rooms of the future are likely to be required to handle greater volumes of data of increasing complexity from new and

advanced sensors [3, 4]. Furthermore, the integration and interpretation of this data may potentially need to be completed with similar or even reduced crew sizes, a drive prevalent in many domains including maritime. A key challenge for future submarine command teams is to effectively manage increasing volumes of data of greater complexity, whilst ensuring that workload is maintained at a level which facilitates optimal performance [1- 4].

A sociotechnical systems perspective offers a theoretical framework for understanding submarine control room functionality [2]. However, advanced technologies are frequently implemented without formal assessment from a sociotechnical perspective. The long service life of submarines often leads to retrospective technological upgrades, without clear consideration of how the relationships between human and technological agents can be maximised. It is critical that the processes which facilitate the effective sharing and co-ordination of information across the control room are understood and that contemporary ways of working are documented [4, 5]. Understanding the distribution and sharing of information within command teams can help to inform the optimal design of control rooms and technologies across many

domains and the manner in which a team is configured and how technology supports communication can also influence their effectiveness.

2 Method

2.1 The Command Team Experimental Testbed

The Command Team Experimental Testbed (ComTET) is program of work tasked with providing evidence-based recommendations for change to optimise the design and operation of submarine control rooms of the future. The program has independently examined and documented current submarine command team functionality and performance to understand current shortfalls and identify the requirements for potential solutions. It has demonstrated how a low-cost mid-fidelity simulator (see figure 1), submarine command team training package, utilising both expert [6] and non-expert [7] operators and a specialist methods toolbox can be designed, built and utilised for this purpose [8 – full description). The simulator is equipped with a range of apparatus for recording communications, operator behaviour and physiology. A series of studies have been conducted with good statistical power, which has produced a body of work which balances ecological validity with experimental control and validity to provide evidence based recommendations for future control room design, operation and capacity [1,5,7,8]. The study protocol received ethical approval from the University of Southampton Research Ethics Committee (Protocol No: 10099) and MODREC (Protocol No: 551/MODREC/14).

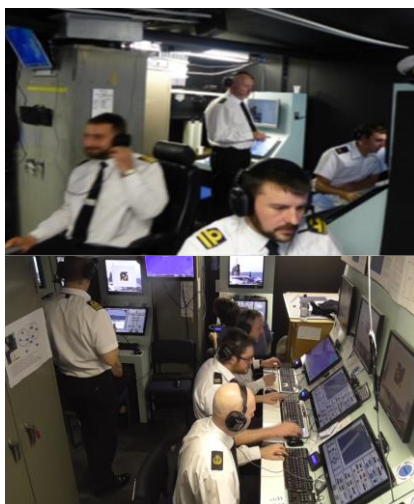


Fig 1. The ComTET submarine control room simulator, for full description see [8]

2.2 The Event Analysis of Systemic Teamwork

A primary method utilised across the program was a new shortened form of Event Analysis for Systemic Teamwork (EAST) method. EAST models complex

collaborative sociotechnical systems through a network approach. Specifically, three networks are considered: task, social, and information (see figure 2). The method is agnostic as to whether agents are human or technological making it a powerful analysis technique for understanding and documenting complex sociotechnical systems. The networks are based on transcriptions of all of the communications in the sound and control rooms. The three networks are developed from the raw data of video and verbal recordings via compilation of static adjacency matrices.

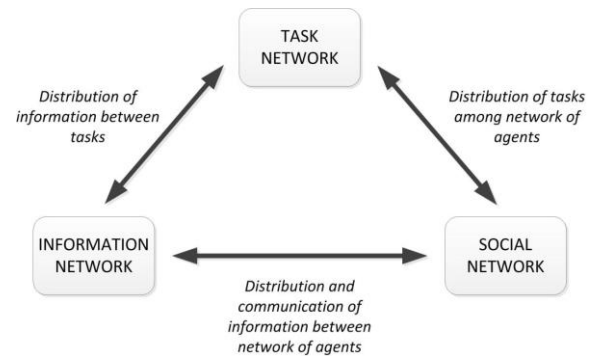


Fig 2. A schematic representation of the EAST method

Metric	Definition
Nodes	Entities in a network
Edges	Pairs of connected entities
Density	Number of relations observed represented as a fraction of the total relations possible
Cohesion	Number of reciprocal connections in the network divided by the maximum number of possible connections
Diameter	Number of hops required to get from one side of the network to the other
Emission	Number of links emanating from node in the network
Reception	Number of links emanating going to each node in the network
Sociometric	Number of emissions and receptions relative to the number of nodes in the network
Centrality	Extent to which network revolves around a single node
Closeness	Inverse of the sum of the shortest distances between each node in the network
Farness	Sum of each node to all other nodes in the network by the shortest path

Fig 3. Overview of global and nodal network metrics

Social networks analyse the communications taking place between the ‘agents’ working in the team. Task networks describe the relationships between tasks, their sequence and interdependences. Finally, information networks describe the information that the different ‘agents’ use and communicate during task performance. The operators (e.g. Officer of the Watch – OOW), information (e.g. classification) and subtasks (e.g. designating contact) are all treated as nodes in networks and their connectivity is assessed. A number of network

metrics are derived from each of the network types affording quantitative statistical comparison, which complimented qualitative visual examination of networks to enable interpretation and understanding (see figure 3). The global metrics describe the composition of the entire network, including its density and cohesion. The individual nodes in the network can also be scrutinised, for example sociometric status is a metric indicating how busy a particular node is in the network, relative to all other nodes.

2.3 Procedure

The work, undertaken by the University of Southampton was funded under the MoD S&T programme and managed by Dstl. A representative submarine control room simulator was built based upon an ASTUTE-class submarine. The construction of the simulator was modular, affording easy reconfiguration of the workspace, consoles, software and communications network. The simulator was comprised of two Sonar Operator stations (SOP), two Target Motion Analysis stations (TMA), a Sonar Controller station (SOC), an Operations Officer station (OPSO), a Periscope station (PERI), a Ship Control station (SHC) and an Officer of the Watch station (OOW). The simulator was equipped with a comprehensive recording suite (e.g., web cameras and ambient microphones), which allowed the recording of all communications that occurred between operatives.

A set of 6 unclassified scenarios (Return to Periscope Depth, Dived Tracking and Inshore operations – all in high and low demand) were designed to capture the widest range of operations submarines routinely complete. It is appreciated that this testing did not include full sensor capabilities or operator numbers, however it was representative with findings offering relative validity. All aspects of the current work were kept unclassified to allow the widest dissemination and review of findings. An 8 hour training package was designed to train non-expert operators to be representative of a submarine command team. This included the basics of submarine operation, the development of a tactical picture, optimal communication structure and specific workstation operation (e.g. a sonar operator tutorial and periscope operator tutorial). A large number of novice participants (drawn from industry as well as the university studentship) for each study (10 teams of 8 individuals were recruited for each study, providing high statistical power). To provide a point of reference, one of the teams recruited from each study was made up of currently operational submariners, used as the ‘gold-standard’ comparator.

3 Overview of Findings

The current paper is summative rather than empirical, providing high-level insights into the work conducted to date. A series of studies have been conducted to examine optimal submarine control room configurations. Initially a baseline configuration was examined. This was constructed to be representative of current platform design

to identify and document shortfalls and inform potential avenues of optimisation. The progression of the studies were data driven and iterative, with empirical evidence informing the design of novel concepts. The novel designs included a co-location configuration, a reduced crew size configuration and a circle configuration, with four studies conducted in total including baseline. The design process was facilitated by steering committee meetings in which domain experts from the Royal Navy, Industry and other relevant partners were invited to critique the designs and provide direction prior to empirical assessment.

3.1 Baseline

The baseline studies examined contemporary ways of working (A-class submarine) to provide an independent assessment of current functionality, shortfalls and opportunities. The baseline studies also provided a comparator against which future studies (e.g. implementing changes such as new sensors or crew size reduction) could be scientifically compared. The primary observations from the baseline studies are documented below.

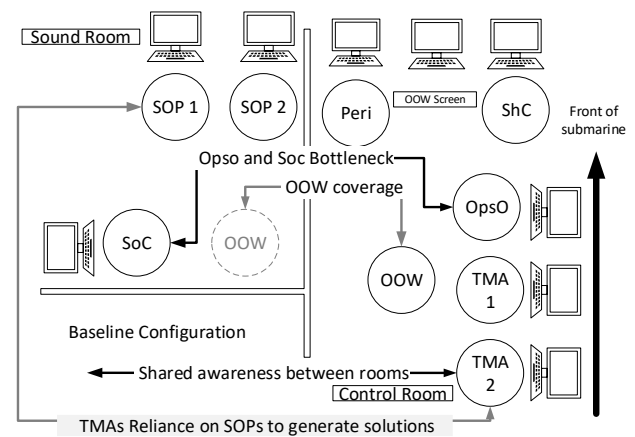


Fig 4. Overview of shortfalls revealed in the baseline configuration

- (1) A communication bottleneck between OPSO and SOC was observed. The communication between these operators was critical in terms of connecting the sound room and control room. This resulted in a delay of critical information being passed from the sound room (e.g. new contact detection) or a backlog of information (see figure 4).
- (2) The distance between the SOPs and TMAs was the largest observed in terms of network composition (i.e. largest number of hops to connect these ‘nodes’). Yet these operators rely most heavily on each other for task completion (e.g. feeding speed estimates into solution).
- (3) The combination of points 1 and 2 above meant that information exchange was not optimal. For example, a SOP could generate a speed estimate, this would then need to be passed/reviewed to SOC, then onto OPSO and then to a TMA operator. If the SOP and/or OPSO were engaged (e.g. liaising with OOW) a speed

estimate could take a great deal of time (i.e. over 15 minutes) to be integrated into a solution from point of attainment.

- (4) The OOW had to seek and frequently request information, pulling information out of the system rather than the information being pushed to him.
- (5) OPSO is often extremely overloaded in terms of information brokering (e.g. for OOW), quality checking (e.g. for TMAs) information fusion (e.g. sonar and periscope) and prioritising (e.g. with SOC).
- (6) Lack of sensor information alignment resulting in disparate information availability (e.g. bearing might be provided by sonar and/or periscope) with this requiring operator intensive decision based integration.
- (7) Difficulty assessing operator workload and task understanding, due to outward facing workstations.
- (8) Presence of engineered production blocking. The current configuration means that operators (e.g. SOPs) cannot always pass or receive relevant information (i.e. as only one operator can talk to SOC at any time).

3.2 Co-location and reduced crew size

The findings from the baseline studies led to the proposal of a co-location configuration in which operators who were dependant on each other for task relevant information were co-located. The intention being to reduce information flow bottlenecks and distribute information handling (cognition) more evenly across the command team where it was appropriate to do so (i.e. maintaining rank structure). The proposed configuration is presented in figure 5 alongside an overview of the shortfalls identified in the baseline studies and how such issues have been addressed in the co-location configuration.

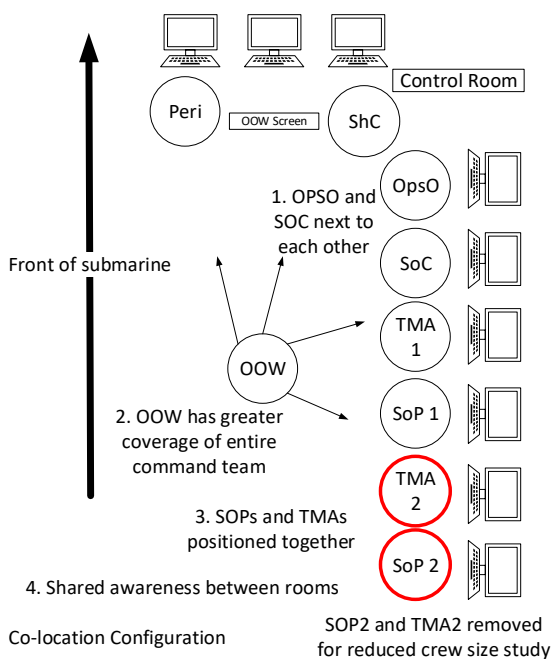


Fig. 5 Shortfalls revealed in the baseline configuration and proposed co-location configuration.

A significant improvement in the volume of tasks completed and efficiency of information transition was observed in the co-location configuration. Information flow was more efficient, although the content of communications remained similar, indicating the new configuration had not adversely effected ‘what’ the command teams did but rather ‘how’ they completed tasks. The success of the co-location configuration, and increase in productivity observed resulted in the decision to examine the impact that crew size reduction had on information flow in the co-location configuration. It was decided to remove SOP2 and TMA2 as these roles had duplication (i.e. spare capacity) and the second operators were seen to complete the lowest volume of tasks in the previous studies.

Despite having two less operators the command team functioned well. In the low demand scenarios the number of verbal communications was greatly reduced from all operators. It appears that the removal of two operators decluttered the communications network and operators did not have to wait for an optimal time to pass information. As observed in the co-location with larger crew size, the communications between SOP1 and TMA1 increased compared to baseline (despite overall communications decreasing), indicating a richer and a more task relevant information exchange. In essence, overall communications were reduced as the newly co-located operators could simply request information as and when they needed it, facilitating the completion of more tasks overall. In baseline, this information was typically required to be passed from SOP to SOC to OPSO before finally reaching TMA. This led to a greater volume of communication but a reduction in task completion.

3.3 Circle configuration

A number of effects observed in the co-location and reduced crew size studies continued with the circle configuration (e.g. increased communications between SOPs and TMAs compared to the baseline). In the circle configuration, however, the volume of verbal communications from the OOW was greatly reduced but the amount of communications received by the OOW remained relatively high. This indicated that the OOW did not have to pull information out of the command team but instead information was being organically fed to the OOW as the tactical picture developed. This differed depending upon scenario demand. In higher demand scenarios the OOW communicated more frequently, prioritising task allocation in a top down fashion. As the OOW could see the entire command team (face-to-face) and their interfaces from the same position, he/she was aware of which tasks were being completed and the operator workload (see figure 6). The OOW did not request information as frequently due to improved awareness of which tasks the disparate members of the command team were completing and their progress. There were less instances of senior operators (OOW, OPSO and SOC) repeatedly requesting information from junior operators as

it was easier to monitor the progress of task completion of junior operators.

The merging of information from different sensors was achieved with much greater ease as the information was available to all operators on large public displays (this helped to improve shared situation awareness). For example, during an inshore operation, if the OPSO was attempting to merge sonar and periscope contacts, the operator could clearly see the two HMIs side by side, as well as seeing the screens and faces of the relevant operators for verification (often non-verbal).

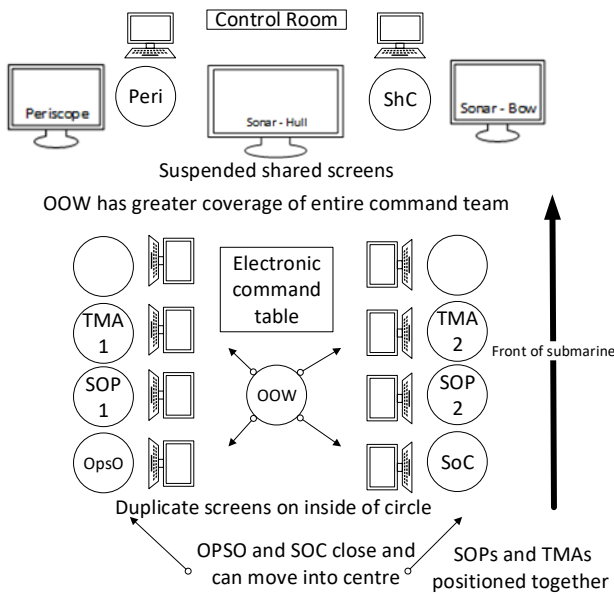


Fig 6. The circle configuration

4 Lessons Learned

The submarine control room has evolved across a century of operations and so represents a high state of maturity but this does not mean it cannot be improved. The ComTET program has demonstrated how evaluation of complex systems from a sociotechnical perspective can reveal shortfalls in contemporary systems. Furthermore, the program has identified a toolbox of methods that can be utilised to evaluate future concepts in a low cost mid-fidelity simulator. The continuing advancement of

technology means there is real opportunity to increase capability as we progress through the digital age. It could also be argued that examination of optimisation from a sociotechnical (rather than solely technical) perspective is a necessity rather than an opportunity. As computer-processing capacities increase the workload requirements placed upon humans could become problematic if future systems are not designed effectively. The implementation of new technologies has the capacity to reduce potential shortfalls but only if the utility afforded by such upgrades is fully realised.

The ComTET program has demonstrated that it is possible to build a low cost mid-fidelity simulator and conduct a series of studies with high statistical power to provide evidence for how submarine control room operations of the future might be improved. The EAST method is a novel way of documenting and quantifying complex sociotechnical systems. It models the functionality of complex sociotechnical systems in a manner accessible to a broad audience. The output of this analysis has the potential to facilitate requirements elicitation for future system upgrades whilst simultaneously forging a common understanding between academic, industry and military partners regarding future aims and requirements. The key findings highlight that collocation of operators highly dependent on each other for task completion creates greater efficiency in terms of information flow and increases command team capacity.

The testing program has also provided early insights into the potential for sensor information integration, role merging, optimal integration of future sensor information/operation and where automation of tasks might best be focused. These findings are outside the scope of the current work, however the empirical data (i.e. information and task networks) are being utilised by industry partners involved in the design of next generation concepts. It is acknowledged that the current work has limitations, most notably that full sensor capabilities or operator numbers were not included in the testing program. Nevertheless, the large sample size attained (over 350 participants in ComTET studies to date) has provided a body of evidence with high statistical power and excellent relative fidelity. The output of this analysis has the potential to facilitate requirements elicitation for future system upgrades whilst simultaneously forging a common understanding between academic, industry and military partners regarding future aims and requirements.

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Chris Parnell – After completing an Engineering apprenticeship and qualifying as a sonar maintainer he served on Diesel and Nuclear powered submarines during a 14 year career with the UK Royal Navy. He received a B.Sc. in Engineering Studies from Portsmouth University while employed with the Defence Research Agency, UK and is now a Dstl Technical Partner for future submarine combat systems.