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Kapittel 6

Human Expertise as Technology

Engine Room Monitoring and Training Systems Enhanced by Human Cognition

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Abstract: This paper presents the findings of a *Cognitive Task Analysis* of expert chief officers on Norwegian merchant and governmental ships. The focus of the analysis is twofold: First, to reveal expert knowledge that the chiefs used to detect technical faults and issues aboard their ships that remained undetected by the current Ship Monitoring System [SMS]. Second, to investigate how this process of monitoring and fault-finding can be automated and implemented in the SMS and engine room simulators through training and assessment. The findings of this study show that information can be lost in the transformation from human on-site supervision to automation and autonomy, and special attention must be paid to the tacit dimension of knowledge. The chiefs had a mindset on heedful performance, and this is shown to be a challenge to the general implementation of automation and autonomy. The concepts of a *detection value-function* and *domain transform* are presented. The use of these concepts is shown to facilitate possible transformations between domains of operation. The findings of this study are somewhat general and can apply to areas like maritime simulators, ship monitoring, remotely operated- and autonomous ships.

Keywords: cognitive task analysis, expertise, ship automation, smart ships, autonomous ships, field theory, situational awareness, maritime simulation, training and assessment.

Introduction

During the last decades, there has been a paradigm shift within ship operations. Due to automation and increasingly complex monitoring systems, crew sizes are reduced, and currently, one-man bridge operation and unmanned machine rooms are common. This trend will probably culminate in future autonomous ships serving fully automated seaports and inland terminals. This will impose necessary changes to the way we train maritime personnel and the way we design simulators and ship monitoring systems. Much knowledge and skills used by engineers and others aboard the ships today is tacit. Disregarding all the obvious technological challenges of this new paradigm, knowledge creation, use, and management will pose a problem for future ship operations as there aboard some ships and in some ports will be no humans with firsthand perceptions and cognition. Ship engines, manoeuvring, and navigation will be controlled by algorithms and computer programs which are improved and reinforced through Machine Learning [ML] and Artificial Intelligence [AI]. Current ship automation is a result of the available body of knowledge about what to measure, and hence which data to collect, and how to process it. This study is about the information that evades current Ship Monitoring Systems [SMS] and addresses the information about potential errors and faults that experienced human operators nevertheless pick up and detect. The focus of this study is to present the tacit knowledge and skills as explicit if possible. If made so, it can be used to improve the future training and assessment of marine and maritime personnel in general and marine engineers in particular.

Historically, sensory systems in engine rooms and elsewhere were static, consisting of sensors, signal conditioning, and a threshold- or window detector triggering an audible and/or a visual alarm. In many ways, current SMS's contain remnants of this paradigm. Although modern sensory systems are based on adaptive signal processing, quite often the sensors themselves remain static (Haykin, 2013; Liu et al., 2011; Sayed, 2003). This is contrary to human sensory systems, which are generally highly adaptive and dynamic. Human operators move around, use tools like night goggles, sonars, and radars, interpolate, and use many other techniques to enhance their sensory inputs and their ability to detect states or errors in the surrounding world.

The scope of this article is to utilise findings in a study of experienced machine room chiefs on how they facilitated the detection of otherwise undetected faults in the engine room by using expertise combined with their perceptions. One possibility that needs investigation is that this knowledge is partly tacit and mostly the property of experienced operators. By using this knowledge to improve sensor systems, combined with the immense processing powers of modern-day computers, this could facilitate the construction of better SMS's and training simulators. Not much work has been published on the collection and use of experience and tacit knowledge to *improve current Ship Monitoring Systems.*

My focus for the data collection will be to *use Cognitive Task Analysis* [CTA] *to uncover tacit and explicit knowledge created by experienced chief engineers.* One further delimitation will be to use the following problematic: *To identify a few cognitive tasks that lead to the detection of some otherwise unattended faults in the engine room and investigate how these tasks could be implemented in the SMS and used in training and assessment.* This also implies that I will restrict the discussion to cognitive tasks and perceptions that are feasible to implement in the SMS. Although not a part of the research problem per se, this study will hopefully provide useful information for anyone working with improving monitoring systems within automation and autonomy, not being restricted to the maritime domain.

Method

A part of the main scope of this study was to use Task Analysis to uncover knowledge in the engine room that was not already utilised in the SMS. Preliminary investigations identified this as *tacit* knowledge (Polanyi, 2009). The early findings also indicated that the tasks involved were almost entirely mental. Because of this, it was decided to do a cognitive task analysis (Crandall et al., 2006a). Not much research has been done on using CTA to improve the SMS, ship automation, or autonomous ship operations, but

there are some research and publications addressing this (Grøtli et al., 2015, 2016). A more comprehensive literature review was considered to be beyond the scope of this study.

Participant Characteristics

The participants were all male Norwegian chief engineers, referred to as 'the chiefs' or 'the informants.' All had more than ten years' experience aboard merchant ships or governmental vessels. They had all mixed ship experience, and one had extensive experience from Norwegian deep-sea merchant tankers. They were all between 35 and 55 years old.

Sampling

One unintentional benefit from the sampling was that all informants currently worked as lecturers within STCW-approved maritime engineers' education. Because of this, they were familiar with expressing cognitive procedures through verbal communication with others. The size of the sample with regards to the overall population of experienced engineers in Norway was not considered an issue in this study. The sample size $n = 4$ was selected because this made a good fit for the focus group interview. Due to logistic issues, this number had to be reduced to 3. One considerable weakness of this study is that more interviews should be conducted with more heterogeneous groups.

Research Method and Data Analysis

The data for this Cognitive Task Analysis were mainly collected during a focus group interview (Morgan & Krueger, 1997). The group was given one main scenario to elaborate: *You are together on a ship, you know the engine room in and out, but one day when you enter you realise that something is wrong, despite none of the alarms being triggered.* Probes were given during the interview to keep the focus on data needed for the cognitive task analysis, and much effort was made to keep the group talking about their individual and joint cognition. The interview was recorded and transcribed

word by word (*Transcription in Action: Representing Discourse*, n.d.), resulting in 9000 words of text. Throughout the interview, Morgan and Krueger's guidelines were followed. Text was not coded digitally, but manually using colour-coding and highlighting to arrange the ideas according to object class. The informants used much seamen's jargon, and instead of addressing this during the interview, I was able to ask the informants some follow-up questions in the following few days. These were not transcribed, but notes were taken. CTA is no one method, but more of a set of practices to provide a framework for retrieving the cognitive processes of one or more tasks (Crandall et al., 2006b; Klein & Wright, 2016a). For this study, it was decided to follow the framework and the procedures provided in Crandall et al. (2006b). Much effort was made to reach saturation during the analysis of data (Corbin & Strauss, 1990; Glaser & Strauss, 1967), and the results are presented categorically according to the physical domain of the detection. The overall approach to this study is to fundamentally follow a naturalistic inquiry (Lincoln & Guba, 1985).

Validity

Gary Klein addresses one fundamental issue of validity that is highly relevant to this study. It is a reference to personal communication with David Woods, and for the sake of clarity, I will quote it directly:

> Woods (pers comm) has raised the ethical question of how a CTA application will be used. He noted that in many instances, the designers of a system want to eliminate the role of the human and are seeking to capture the human contribution to the task in a small set of rules that can be turned into an automation of a task. If a CTA application is shallow, and fails to capture the richness and subtlety of the cognitive skills, then it will be easier to dismiss the importance of the human operator, which can lead to serious consequences (Klein & Militello, 2001, p. 189).

Methodical limitation and weakness to the study

As previously mentioned, this research calls for studies on more heterogeneous groups and informants. The informants used in this study may have a more methodical approach to inspection and fault finding than what is typical or what would be considered average behaviour. All marine engineers are educated within the same framework. Some start their careers as third engineers, while others leave the maritime domain at an early stage. My informants advanced all the way to chief engineers and ended their careers in academia. Their highly motivated and goal-seeking behaviour might be a desired trait with regards to training and assessment, but it could be difficult to achieve with some personnel.

This will probably have no negative implications for implementation in the SMS but must be considered when using knowledge gained in this research for training and assessment of marine engineers. This includes implementation in engine room simulators and their derivatives.

Results

The informants provided little information about visual perceptions and knowledge. However, there were many cues about the visual aspects of being in the engine room: the importance of good lighting, neatness and tidiness, and the use of bright paints. This might relate to the idea of the general appearance of the ship and the identity of the crew as an antidote to the general working conditions in the engine room (Lundh et al., 2011). One informant talked about how important it was to have a clean and orderly engine room to facilitate the detection of leaks. In general, it seems that the chiefs considered the detection of visual faults as less demanding and not requiring any special experience. Oil spills on the engine room floor or leaky steam pipes are, after all, very easy to detect, even for the inexperienced operator.

Even though it will be quite feasible to implement visual detection in a SMS through the use of cameras, either ordinary or infrared sensitive, and

off-the-shelf image processing software, I will omit the discussion of visual information for the remainder of the paper. The findings in this study provide essentially no new knowledge about processing visual data within the area of ship automation or maritime human factors.

General Cognition

It was no surprise to discover that the overall cognition within the engineer's community aboard the ship was shared and distributed. They utilised social interaction to improve their knowledge about a given technical problem or fault. They sought support from others to reinforce their knowledge. The initial detection of an issue might be on the individual level, but the overall processing was soon brought to the community level. This very much confirms the findings from other studies of communities of practitioners (Brown & Duguid, 1991; Gherardi & Nicolini, 2000; Klein, 1999; Lave & Wenger, 1991), and studies of maritime crews (Hutchins, 1995). More recent understandings and models of Situational Awareness [SA] also support the relevance of these findings of chiefs operating as agents in complex sociotechnical systems (Endsley, 1995, 2015; Stanton et al., 2015, 2017; Winsen & Dekker, 2015). This will be further addressed in the discussion, but the findings imply that human perception in the engine room is not essentially individual, but part of a greater sociotechnical system.

Another important finding regarding the general cognitive workload amongst the interviewed chief engineers is that they made their own goals and sub-goals (G. Klein & Wright, 2016b; Yates, 2007). These were an addition to their assigned goals as a part of their job instruction. One informant talked about a case where he and other engineers set out to make an extra effort to improve the general condition of the main engine and the engine room aboard a particular ship. They succeeded to some extent, and the shape of the engine room improved.

In addition to these goal-oriented tasks, the findings in this study indicate that the maritime engineers also endured a sensemaking process while working. This is in compliance with current research within organizational and management theory. If I can make a justified guess regarding

which sensemaking paradigm seemed best fit to explain what was observed, I would choose to go with Weick's sensemaking framework (Weick, 1969, 1995; Weick et al., 2005), although Klein's model of Naturalistic Decision Making, Recognition Primed Decision Making, Data/Frame Model of Sensemaking, or others might be more predominant within human factors research (Klein, 1997; Klein et al., 2007; Klein, 1993, 1999; Zsambok & Klein, 2014).

Heedful Interrelating in Engine Rooms

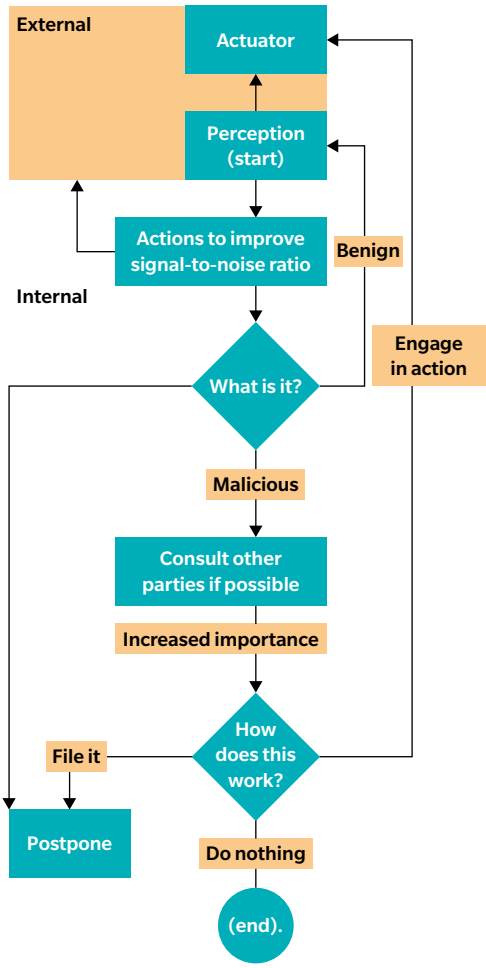
The perception and processing of perceptory information was very much a part of the day-to-day inspection and supervision of the engine room. Some of this was governed by mandatory rules or checklists, and some were not. The informants made great effort to stress the importance of doing something extra. They noted that some higher-ranking officers made them excel, while others made them underachieve. They all agreed that it was very important to have a mindset that strived for the best possible performance. Hence the paraphrasing of the title of Weick and Roberts' seminal paper in the heading of this chapter (1993). To have a mind set on performing at one's best is sometimes addressed as performing with heed (Ryle, 1949). Accordingly, the findings show that it will be important to maintain a heedful mindset in future autonomous and automated ship operations. The obvious issue to discuss will be where this mindset will reside, if anywhere, when engine rooms are void of humans.

When Curiosity Saved the Cat

Figure 6.1 provides a model of the cognitive process of fault detection, analysis, and correction that was identified as a result of this study.

Figure 6.1

Cognitive chart of processual fault finding aboard a ship using expertise.



Several individual incidents were studied, and all shared a common starting point in being initiated by some sort of mental trigger. This trigger evoked the curiosity and desire to pursue the incidents and gather information. Curiosity is a known driver for human behavioural change and invokes the desire to explore (Berlyne, 1950, 1966; Loewenstein, 1994). Although many different incidents were identified and analysed, they shared a common mental model describing the same fault-finding process, but different perceptual triggers. For the sake of clarity, the identified triggers are listed by their physical domain:

Sound

The informants listed several issues within the ship and engine room that were detected by hearing, and these were not detected by the SMS initially: faulty bearing in one of two main gearboxes, missing tooth in thruster tooth wheel, faulty air compressor, and faulty inlet valve in diesel engine. In the first three cases, the crew decided to intervene, and the collateral damage was significantly reduced. In the last case, the chief engineer decided not to intervene, resulting in a total engine breakdown. All cases shared a common trigger in a change in the audible spectrum of the sound. Some of these changes were subtle, and some were highly audible. All informants agreed that the criteria for successful detection were proportional to the overall experience of the observer and the rate of change of the audio spectrum over time, providing the following *detection value-function*:

$$V(Q, S, t) = Q \bullet \frac{\Delta S}{\Delta t} \quad (1)$$

Where V is the value of the detection function, Q is the relative experience of the observer, S is the output of the Power Spectrum Density [PSD] function of the sound over all frequencies, and t is time. The PSD is a function of the throttle [speed] and trim of the ship, and possibly also weather conditions. The latter was not addressed during the CTA. The formula (1) is a suggestion based on the empirical knowledge gained from the CTA with the informants. It shows that it is not as simple as comparing consecutive Fast Fourier Transforms [FFT] of audio samples to detect any issues or potential faults aboard the ship. The FFTs must be compared to samples obtained during similar load conditions to the ship.

Heat

Two different cases where the informants sensed the heat in the environment were identified: Thruster overload due to a faulty or worn-out bearing, identified by heat radiation when approaching the thruster shaft compartment, and more general overheating conditions when entering engine rooms. All informants agreed that maritime engineers develop a high sensitivity to temperature and draught over time. One stated that he was able to discriminate temperature deviations of less than one centigrade. All informants agreed that the criteria for successful detection were proportional to the overall experience of the observer and the rate of change of temperature over time, providing the following value-function:

$$V(Q, T, t) = Q \bullet \frac{\Delta T}{\Delta t} \quad (2)$$

Variables are the same as in (1), except for T which is the temperature. All information collected in this study shows that the informant considered T a free variable not showing any dependencies on any ship performance parameters.

Vibration

The perception of vibration was essentially based on gravity and the coupling the informants could feel through their feet or whatever part of their body was in contact with some surface. Two different cases based on the sense of vibration were described: the sense of vibration in the body when lying stretched out on the bed, and the perception of an anomaly in the engine performance from a remote location far from the engine room.

The first case was basically the day-to-day experience the crewmember had of being aboard the ship. Through increased experience, they gained increased sensory knowledge of how the ship vibrated under different speed, trim, load, and weather conditions. The other case was a potential disaster, as it was the regulator that controlled the speed that was stuck at full throttle while the ship was approaching a port. The chief reported, 'it didn't feel right,' realising moments after that the speed was way too high for the current situation. He telephoned the bridge seconds before the mate in charge also realised the malady, and together they were able to correct the speed and save the ship from a potential disaster.

Mechanical Force

One case was reported: One informant talked about how the applied force used to open the door into the engine room was a measure of the relative air pressure in the room. The door opened outwards [they always do], and the air pressure in the engine room relative to the outside determined the force necessary to open the door. By entering and leaving through the door several times a day for a long period, the chief reported that the procedure imposed a certain feel. A tacit analysis of this feeling provided him with information about the ventilation system that was valuable for assessing the state of the system. If the feeling of entering the engine room was abnormal, a trigger

was set, and he knew that something was wrong, urging him to find out more about the current situation. Possible faults that were identified during the interviews were: Fans running in the wrong directions due to swapped phases in the wiring, tripped thermal safety switches, and faulty fan motors. Many of these faults were described as incidents due to insufficient overhaul and/or maintenance procedures.

Elements and Chemical Compounds

Abnormal smell identifying fumes in the engine room were the first triggers the informants discussed. These were the smell of fuel and the smell of coolant fluid. These smells are rather distinct and are probably a part of the smell within the engine room all the time. However, the informants were able to detect small leaks by experiencing a change in the smell within the room. All informants agreed that this was not to be expected from less experienced engineers, and they all listed a range of different incidents during their years at sea. Coolant fluid leaks would be detected by the SMS when the engine would eventually overheat, which was far from desirable, but fuel leaks were almost never detected by the SMS.

Sensory Synthesis

During the data analysis, there were indications that the informants synthesized data, or possibly information, gathered from different sensory inputs to identify an issue or fault. From these indications, it would be very difficult to make any conclusive models on how this was applied and used. Because of this, data synthesis is referred to as the informants mostly described it; as a certain *feel* or *feeling*. However, it is important to note that this was a wording that was fairly often used and referred to during the focus group interview and follow-up questions afterwards.

Experienced but not too Comfortable (Shaken but not Stirred)

The main focus of the CTA was to reveal the knowledge and the skillset that experts used to find faults otherwise not detected by the SMS. This, in turn, led to the obvious question: What is an expert? As it turned out, this resided

in four requirements with the informants: i) Expert knowledge and skills: From my analysis, it seems clear that when the informants talked about experience, they mostly meant expert knowledge. ii) The expert needed a certain amount of time aboard the specific ship to develop a reference frame-set of the environment in the ship in what can be designated a normal setting. iii) All informants agreed that it was an advantage that the experts rotated among ships and did not stay for more than three years on one ship. If they did so, they would dwell in a too comfortable zone. The ship needed a certain amount of turnover and fresh minds from time to time. iv) All informants agreed that it was important that one important property of their expertise was a certain level of self-confidence. All informants reported incidents where they confronted or disagreed with ship-owners and others but did so with confidence because they considered their expert knowledge and first-hand information superior.

Discussion

A good starting point for discussing the findings in this study can be to look at the difference between experience and expert. At its core, experience is ambiguous (March, 1987, 2011). One of the key challenges for any operator, or some may prefer agent, is to discriminate between possible ways to reach a goal. These possibilities are partly known to the operator through acquired experience, and partly through ingenuity, creativity, intelligence, and further. The expert will use previously untested possibilities to reach a goal. Novices almost never do that. The Dreyfus & Dreyfus five-stage model for skill acquisition is well known within pedagogics, and in one paper Stuart Dreyfus describes the expert like this:

> The proficient performer, immersed in the world of his or her skilful activity, sees what needs to be done but decides how to do it. The expert not only sees what needs to be achieved; thanks to his or her vast repertoire of situational discriminations, he or she also sees immediately how to achieve this goal. Thus, the ability to make

> more subtle and refined discriminations is what distinguishes the expert from the proficient performer (Dreyfus, 2004, pp. 179–180).

Initially, the Dreyfus brothers worked on mapping the mental activities involved in skill acquisition when they introduced their model (Dreyfus & Dreyfus, 1980). The model can be criticised for lacking empiricism, but it provides a good fit to the requirements for expert performance that the chiefs provided.

One old saying among practitioners is that experience is a poor teacher, and this is the reason for having procedures (March, 2011). The procedures provide the starting points for novices, and this is essentially the core of the Dreyfus model: how these procedures evolve into more and more complex knowledge and skills until they are redundant and not used. Skills and knowledge are used to adapt problem-solving and fault-finding behaviour to the relevant situation. The chiefs, in their day-to-day activities, become goal-seeking as opposed to procedure-following (Powers, 1973). The findings of the CTA showed that they had a mindset focused on the overall performance of the ship, as there were mostly no procedures to follow to detect the issues and faults addressed in this study. This is also very much in line with the concept of meaning (Bruner, 1990; Frankl, 1992). The chiefs engaged in activities that gave the most meaning to their work as chief engineers, and as experts, they used the best tools available to support their day-to-day decision-making and eventually make good decisions (Klein, 1999).

Tacit is as Tacit does

Knowledge has for some time been categorised as either tacit or explicit. This originated in Michael Polanyi's work on tacit knowledge in the mid-twentieth century (Grant, 2007; Mitchell, 2006; Polanyi, 2009), and continued with the work of Takeuchi, Nonaka, and others at The University of Tokyo (Bennett, 2001; Nonaka, Toyama, & Konno, 2000; Nonaka, Toyama, & Nagata, 2000). Both schools centred around the principle of a tacit dimension to knowledge, not a division. Central to the second school of knowledge creation was also the notion of BA, which means: Being in the shared place where knowledge is created (Nonaka & Konno, 1998). In other words, it is more than just human interaction or a physical space; it might just be an email server or a Content

Management System [CMS] situated entirely in the virtual domain. Polanyi's original idea was that all knowledge cannot be reduced to rules. Explicit knowledge is easy to transfer through narratives and modelling, whereas tacit knowledge will always be more or less compromised during transfer. This again was founded in Polanyi's basic notion that the human mind can never be replaced by computers (Polanyi, 2009). Polanyi, in turn, influenced Hubert Dreyfus' thinking and his standings about AI (Dreyfus, 1972, 1992; Haugeland, 1996). Then again, as it turns out, we are back where we started: With expertise. All expertise cannot be reduced to a simple set of rules, and not within all dimensions.

The Tacit Dimension

In the results section of this paper, it was demonstrated that some of the core knowledge the chiefs gained and used to detect faults aboard the ship could be reduced to some relatively simple 3-variable functions. These functions had a variable, *Q*, which was to represent the relative experience of the observer. Initially simple, a scaling factor to increase or decrease the value of the detection function. It was designated *Q*, which is a well-used designator for *quality*. *Q* would be a measure of the expertise of the observer. However, the value will also have to encompass factors like traits, states, physical shape, and so on. Everything that could enhance or compromise the observer's ability to detect. The findings show that these were factors that were important for the chiefs. As it turns out, *Q* should be an *n*-tuple, or if we stay with the heading of this section, it will be in *n*-dimensional Euclidean space. The tacit dimension will be one of the dimensions in n where $n \in N$. Despite this, *Q* started out as a scalar and can be treated as such to be $Q = |Q|$.

The *Q* in these functions share a commonality with any variable in any function or equation modelling human behaviour. The *P* in Lewin's equation, which despite its popular name is a function, is also one of these variables (Lewin, 2013):

$$B = f(P, E) \quad (3)$$

The commonality is that when replacing the human in a process and moving the person's work function into the digital domain, these variables will of course be replaced by something else. It is not the human behaviour as such that is wanted in these processes. It is not desirable to

simulate the human behaviour, but the result of human behaviour. The chiefs were, as experts, goal-seeking, and that is an important finding from this study. Goal-seeking behaviour provides for some interesting opportunities within AI.

The Domain Transform

The autonomous ship will not be an ordinary ship with autonomy, but more likely a wholly different creation (Rødset, pers. comm., 2017); see also: (Rødseth & Burmeister, 2012; Rødseth & Tjora, 2014). If I follow Rødset correctly, he is more focused on the operations of the ship and the many more possibilities as compared to ordinary ships. But there is also a different way of deducting the differences: Conventional ship operations can be viewed as a purposeful spatial time-dependent sociotechnical system (Ackoff & Emery, 2005; Emery, 1978; Trist & Bamforth, 1951). One or many dimensions of this system are human; the tacit dimension, social dimension, governance, heed, traits, and so on.

Moving from a system with humans to one without can be seen as a transformation from $R^n \rightarrow R^m$. The term m denotes the reduced set of dimensions when the human dimensions are removed. Present conventional ship operations can be designated as the human domain, and autonomous ship operations can be designated as the autonomous domain. It is demonstrated here, and in the results section of this paper, that moving from one domain to the other is not simply a transfer of numbers, but a transform of space that contains a sociotechnical system. For the sake of clarity, I will name this a Domain Transform [DT].

Unknown or unforeseen but still heedful

Initially, autonomous ship operations will be a case of applying new knowledge to new technology. Both are, of course, grounded in years of experience doing conventional ship operations. The informants were goal-seeking, and in that process, looking for the unknown or unforeseen. Within high reliability organizations, this is a task within managing the unexpected (Sutcliffe & Weick, 2006; Weick, 1987). The CTA revealed that this was very much what the chiefs had their mindset on. Having established the DT, it is easy

to see that maintaining their heedful performance will pose a challenge. The CTA indicated that heed and mindfulness were drivers for their day-to-day activities.

Tasks improved by technology

The chiefs interacted with the surroundings and technology to improve their perception. The CTA showed that their mindset was very often set on inspection. Inspection is one of the current professions that has changed at an amazing pace during the last few decades. Inspectors currently use robotic snakes for pipeline surveillance, AUVs and ROVs for subsea inspection, drones for power line inspection, and many more. We are at the brink of a revolution within automation and autonomy, improving operations within maritime and most industrial and governmental operations. Traditional crew manning is reduced by implementing and using more and more digital solutions and AI. AI is not human intelligence, and it lacks affect (Haugeland, 1996, 1998), restraining heed and more to be a part of the design of the system and not an operational part. Hence, it is important not to downscale the importance of the heedful interrelation between the engineers in engine rooms when designing autonomous or remotely operated systems.

The discussion on the detection value functions in the results section can be made generic to any detection due to a rate of change detected by human perception in any domain:

$$V(Q, f, t) = |Q| \bullet \frac{\Delta f}{\Delta t} \quad (4)$$

Where V is the value of the detection function, Q is the relative experience vector of the observer, f is the physical property function that changes, and t is time. Its usefulness must be tested by practical implementation.

Conclusion and Acknowledgement

In this study I have identified tacit knowledge used by marine engineers to identify faults not detected by ship monitoring systems. Several cognitive tasks

performed by the chief engineers that can be implemented in the SMS and in training and assessment are presented. Mathematical models and algorithms are presented for implementation in systems and for training and assessment. This is new knowledge, and it is true about the marine engineering domain, but must be accompanied by more research in other domains to make it more general within other areas of human fault finding and supervision, and to concepts like Situational Awareness.

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