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# Human Co-Agency with Technical Systems: Investigations of Modelling Frameworks

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**To Birgit and Idunn**

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**Executive Summary**

This thesis is about the conceptual frameworks and models that we use to understand human performance in technical work situations. It represents both theoretical and empirical approaches to the issue of how we can conceptualize the human operator as a controller embedded in an environment with technical applications. The thesis starts with an experimental test of ergonomics recommendations (Article I) that many designers use to design control input devices in technical interfaces (e.g. Kroemer & Grandjean, 1997). The article shows, by using measures of goal-directed use (rather than static tasks), that the adherence to ergonomics recommendations may not necessarily entail good or optimal performance. This also means that the models we use to design for human performance must take into account the dynamic nature of the task performance, rather than static factors of that work performance.

The thesis then continues with a phenomenologically inspired conceptualization of the human mind as an embodied agent aimed towards controlling actions in the world (Article II). This view is then implicitly brought on into observations of high-speed craft navigation and manoeuvring, where the human operator's control strategies are investigated (Article III). The last article (Article IV) is a direct continuation of the observations of high-speed craft operation and presents video recordings from conversations during navigational exercises. The article discusses the use of the control situation framework to model the operator's models. The adaptation of expert operators is accountable to an ecological affinity which reflects perception-action based experience with the manoeuvring of the high-speed craft in question.

Taken together, these articles show a time-line of the building up of a dynamic model of the human controller that is embedded in a world consisting of ever-increasing technical complexity. The focus in the articles in this thesis (except for Article IV) is primarily on the operators and the *understanding* of the operators' perspective as a situated agent that is immersed in the unfolding co-agency of technology, environment and humans. The operator's understanding and conceptualization of the given situations that unfold in technically mediated work are of critical importance when it comes to understanding how one should model the operator. The problem lies in apprehending the operator's experience as it affects, and are affected by, the dynamic work flow of the joint cognitive system. The overarching aspect these articles point to the need to model the human operator as both separated and integrated part of the technical system.

**Sammendrag**

Denne avhandlingen omhandler de konseptuelle rammeverk og modeller som vi bruker for å forstå menneskelig arbeidsprestasjon i en teknisk kontekst. Den representerer både teoretiske og empiriske tilnærminger til hvordan vi kan konseptualisere den menneskelige operatøren som en kontrollør som er omgitt av et miljø med tekniske systemer. Avhandlingen starter med en eksperimentell test av ergonomiske anbefalinger (Artikkel I) som mange designere bruker for å utforme tekniske grensesnitt (f.eks. Kroemer & Grandjean, 1997). Artikkelen viser gjennom å teste målorienterte handlinger (heller enn statiske oppgaver) at design i henhold til de ergonomiske standardene ikke nødvendigvis medfører en optimal prestasjon. Dette betyr at de modellene vi bruker for å designe for menneskelig prestasjon må ta høyde for arbeidsoppgavens dynamiske natur, heller en å fokusere på statiske elementer ved arbeidsoppgaven.

Avhandlingen fortsetter så med en fenomenologisk inspirert konseptualisering av menneskesinnet som en kroppsliggjort agent som søker å kontrollere handlinger i verden (Artikkel II). Dette perspektivet er så anvendt i observasjoner av navigasjon og manuvrering med hurtigbåt, hvor man studerte den menneskelige operatørens kontrollstrategier (Artikkel III). Den siste artikkelen (Artikkel IV) er en direkte kontinuasjon av observasjonen fra hurtigbåtnavigasjon og presenterer videoopptak av samtaler mellom navigasjonspersonnel under navigasjonsøvelser. Artikkelen diskuterer bruken av kontrollsituasjonsrammeverket for å modellere de modeller operatøren bruker for å kunne kontrollere båtens bevegelser. Tilpasningen gjort av erfarne operatører kan beskrives som en økologisk affinitet som reflekterer persepsjons-handlingsbasert erfaring med å manuvrere hurtigbåten.

Sett under ett så viser disse artiklene en tidslinje for etablering av en dynamisk modell av den menneskelige kontrolløren som er omgitt av et miljø som består av økende teknisk kompleksitet. Fokuset i artiklene i denne avhandlingen (unntatt artikkel I) er primært på operatøren og på *forståelsen* av operatøres perspektiv som en situert agent omgitt av et miljø hvor interaksjonen mellom teknologi, miljø og mennesker sammen utgjør grunnlaget for å kontrollere en artbeidsprosess. Operatørens forståelse og konseptualisering av en gitt situasjon som utvikler seg i en teknisk mediert arbeid er av stor viktighet for å forstå hvordan man skal modellere operatøren. Utfordringen ligger i å forstå hvordan operatørens opplevelse påvirker, — og blir påvirket av, den dynamiske utviklingen av menneske-maskinsystemet. Det overordnede aspektet artiklene i denne avhandlingen peker ut er nødvendigheten av å modellere den menneskelige operatøren som både en separat og en inkludert del av det tekniske systemet.

# Article Overview

**Article I:**

    Øvergård, K. I., Fostervold, K. I., Bjelland, H. V., & Hoff, T. (2007). Knobology in use: An experimental evaluation of ergonomics recommendations. *Ergonomics*, 50(5), 694-705.

**Article II:**

    Øvergård, K. I., Bjørkli, C. A., & Hoff, T. (2008). The bodily basis of control in technically aided movement. In S. Bergmann, T. Hoff and T. Sager (Eds.), *Spaces of Mobility* (pp. 101-123). London, UK: Equinox Publishing.

**Article III**

    Bjørkli, C. A., Øvergård, K. I., Røed, B. K., & Hoff, T. (2007). Control situations in high-speed craft operation. *Cognition, Technology, and Work*, 9, 67-80.

**Article IV**

    Øvergård, K. I., Bjørkli, C. A., & Hoff, T. (submitted). Models and Control Strategies used by Experienced Marine Navigators. *Cognition, Technology, and Work.*

**Preface**

This thesis is the result of fruitful collaboration with several knowledgeable researchers who I had the pleasure of working with. The thesis consists of four articles and an introductory chapter that describes the relation between the articles and the possible theoretical and methodological implications when the four articles are seen as a whole.

The introductory chapter outlines briefly the theoretical basis for the modelling of human-technology systems. Special emphasis is given to the relation between modelling the operator as such, and modelling the whole sociotechnical system.

Article I presents an experimental study of the effect of ergonomics recommendations for the design of control knobs on operator performance. The article was written in collaboration with three co-authors. I was in charge of all aspects of the research process (planning, literature review prior to the experiment, data collection, data analysis and primary writing). The experimental equipment and the graphical user interfaces programmed in flash was designed and assembled by the third author (H. V. Bjelland).

Article II presents a philosophical and theoretical approach to the understanding of the human operator as an active, extended controller of activity. The main focus is on how the human operator's ability to control movement is altered by technical transport systems. The article was written in collaboration with two co-authors. I was involved in all aspects of the research process and was responsible for the literature research prior to the writing, the writing of the article and the theoretical contents.

Article III presents observations of high-speed craft navigation in confined waters. The article elaborates on and extends Petersen's (2004) control situations framework to include the operator's control strategies. The article was written in collaboration with three co-authors. My contribution was related to participating in data collection and as a secondary writer. I am jointly responsible for the theoretical content together with C. A. Bjørkli who was the primary writer. Data analysis was done by C. A. Bjørkli.

Article IV presents transcriptions of communication on the bridge of a high-speed craft during navigation and manoeuvring in difficult and critical situations. The article was written in collaboration with two co-authors. I was directly involved in all aspects of the research process (conceptualization of research, data collection, data analysis, theoretical content and primary writing).

<center>**Introduction**</center>

Research on human-technology systems has for decades acknowledged the importance of modelling the characteristics of the users of technical systems (e.g. Card, Moran & Newell, 1983). The reason for this is the realization that technical systems must not only design for the physical characteristics of human operators, but also the user's cognitive characteristics (Norman, 2002; Vicente, 2004). The models of the users are dependent upon the contents of the work process that is modelled. This means that some models are more appropriate for describing a given set of phenomena than other models (Woods, & Hollnagel, 2006). The models used by researchers guide their observations and conceptualization of work situations (Hollnagel, & Woods, 2005, p. 50). The underlying conceptualizations and the derived models are important because the models can guide the design of technical systems (Woods, 1998). The design of work domains have serious consequences for the work performed by human operators in sociotechnical systems (Perrow, 1999; Casey, 1998). In general, one can differentiate between two types of scientific models of human-technology systems – the *componential* and the *systemic*. These models address different aspects of the human-technology system, and thus also give different solutions to the practical problems of human factors research.

## The componential view of human-technology systems

The first general type of models is the *componential models* of human-technology systems. They assume that the behaviour of a system[1] is principally predictable from the behaviour of its components (Card, Moran & Newell, 1983; but see Hollnagel & Woods, 1983/1999; Dekker, 2005). Hence, by knowing the behaviour of each individual component, it is possible to determine the behaviour of the whole system. This leads to an approximation of the whole system's behaviour based on the notion of human operators *plus* technical system *plus* interface characteristics. Thus, the whole system's behaviour is understood as a simple additive interpolation of the components' behaviours.

The componential view has often been used in the modelling of elementary cognitive processes (see e.g. Townsend & Ashby, 1983; Fodor, 1983). The ontological basis for this view is most prominently present in the information processing approach to human cognition

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[1]A *system* does not have any default size, but is defined by the boundaries the modeller sets and the components that are included within the system. This means that a 'system' can include any research object and the parts of its surroundings. For example, human working memory may be seen as a system that interacts with an environment, or one may view a human as a system which interacts with its environment, or one may see the human-environment as a system in its own right (see e.g. Gibson, 1979).

and behaviour (Gardner, 1985; Fodor, 1983). The information processing approach is a componential approach that is based on a dualism between mind and body, body and environment, and mind and environment. It had (and to some extent still have) the hegemony in psychological research for several decades (Gardner, 1985). The basic argument for maintaining the dualism between mind and body was based in the assumption that the world was 'under-specified' or 'impoverished' which meant that the sensory input stemming from the environment was not enough to signify an object, but rather that the interpretation of the sensory input had to be supported by the use of internal representations (Marr, 1982). Since the information-processing theorists believed that sensory input had to be supported by internal representations, the structure and layout of the environment had little or no relevance for human behaviour since the behaviour was essentially guided by internal representations (Hoff, 2004). Thus, the environment (and hence also technical systems) is removed from the analysis of human cognition (see Gardner, 1985, for a historical note). This understanding leads to a view of technical systems as neutral, detached objects, which are independent of the results of the human operator's behaviour. The technical system becomes a passive instrument for use, and is not viewed an active partner in the interactive process (Ihde, 2002; Dekker, 2005).

The separation between the environment and the human operator can be seen in several of the information processing models used to specify human behaviour and interaction with computers. Specific models of human functioning involve the description of (hypothetical) internal information processing. This internal information processor is divided into different modules corresponding to the different subsystems of internal information processing (the perceptual system, the motor system and the cognitive system) where each of the stages have their own memories and processors[2] (e.g. Card, Moran & Newell, 1983). These information-processing models involve the description of constraints on, as well as the work performed by each of the subcomponents (mostly response times and information processing capacities; Townsend & Ashby, 1983). The general output of the system can then be estimated by adding up the calculations performed by each of the subcomponents (Card et al., 1983; see also Hamilton & Clarke, 2005 for a recent use of this type of modelling). The environment is only seen as interesting to the degree that it gives sensory input to the

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[2] Note that the terms 'processors', 'information processing' and 'modules' involve an analogy to computers and the way computers work.

information processing modules (Hoff, 2004)[3]. This means that faulty decisions or actions can be attributed to internal processing mistakes in the encoding, storage or retrieval of relevant information (see e.g. Reason, 1990, p. 12, and, Reisberg, 2001, p. 204ff, for a thorough description) and not to the layout of the environment.

The dualistic perspective on the relation between human cognition, the body, and the environment has also formed the theoretical and ontological basis for the understanding of human-technology systems (Hollnagel & Woods, 2005). The dualistic ontology implies that humans and environment (machines) are both physically and functionally separate. Following these assumptions, system errors then becomes a question of man *or* machine. This perspective is explicitly formulated in the approach to accident investigations that has been termed "the old view of human error" (Dekker, 2002, p. vii; see also Dekker, 2005). The "old view" approach implicitly assumes that the human component can explain system mishaps according to the formula: Human error = $f(1 – $ technical failure$)$. This leads to the proposal that if there is no technical malfunctioning that can adequately explain the mishap (e.g. technical failure = 0) then the conclusion must be that human error was the cause of the accident (Dekker, 2005). Thus, if one accepts the premises for the componential view, it is principally possible to understand the joint functioning of humans and machines as a product of 'human *plus* machine' (as can be seen in the additive models in Card et al., 1983). Degraded system performance can therefore be understood as being caused by poor performance in either the human or the technical component.

However, the growing complexity of current technical systems have given indications that the relationship between humans and technology now have become so intricate that the componential view is no longer a good model of human-technology systems[4]. A sole focus on the behaviour of a system's components does not help in the understanding of the historical and systemic contributions to performance in complex sociotechnical systems (Dekker, 2002, 2004; Perrow, 1999). This realization has pointed to an extension and reformulation of the unit of analysis in human-technology systems leading to a systemic view of human-technology systems (Hollnagel, & Woods, 1983/1999).

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[3] The end of the 1980-ies saw a decline of explicit internal information processing models and rather turned towards the relation between the human and the technical system (see. Reason, 1990, p. 26ff, for a summary of such models).
[4] Information processing models are not bad models as such. These models only work better on other levels of analysis, such as predicting human performance in constrained or experimental tasks (e.g. the expected reaction times to train signals; Hamilton & Clarke, 2005; Øvergård, Bjørklund, & Hoff, 2006).

The systemic view of human-technology systems

The systemic approach to human-technology interaction was termed Cognitive Systems Engineering (CSE) by Hollnagel and Woods in 1983 (Hollnagel & Woods, 1983/1999). This research paradigm began as a reaction to the componential perspective which categorized humans and technical systems as separate components that are assumed to work according to mechanistic properties (Hollnagel, & Woods, 1983/1999). It is a general agreement that complex sociotechnical systems can be said to consist of mainly three components: Humans, technology (including interfaces) and environment (Bridger, 2003; Hollnagel & Woods, 2005). Even though the components of a system can be described as separate object (as nouns – *a* human, *a* machine and *an* environment) it does not entail that the components are ontologically or functionally separate when it comes to the goal-directed work practises that underlie system performance. The goal-directed activity effectively joints the physically separate components into one functional unit (Hollnagel & Woods, 2005). When observing real-life sociotechnical work domains it is clear that the complex developmental trajectories that contribute to the sociotechnical system's performance cannot be separated into human, technical or environmental aspects.

This has led to a focus on the *functional unity* of sociotechnical systems meaning that the unit of analysis is the goal-directed adaptation of *the whole system*, which involves the coordination of activity across the system's components (Hollnagel, & Woods, 2005; Vicente, 1999). The unit of analysis is enlarged to involve not only the behaviour of individual components, but to cover the co-creation and coordination of activity across humans, technology and environment – it becomes a Joint Cognitive System (JCS) (Hollnagel & Woods, 1983/1999, 2005). This means that the technical system is no longer seen as a neutral object but as an active contributor to the JCS output. Hence, we must analyse and model human-machine systems as a functional unit, and not as separated and isolated components (Dowell & Long, 1998).

The whole system's outcome is seen as an emergent process, where each part contributes to the final process, but no single component is causally connected with the outcome of the whole system (Vicente, 1990; Hollnagel, 2001; Hollnagel & woods, 2005). Control in human-machine systems is not an aspect of either of the system's parts, but is an emergent product of the coordination of work across the systems components (Hollnagel, 2001). This notion of emergence comes from studies in systems science that show that the whole is larger than the sum of its parts and that the whole follow a different set of rules than

those that guide the behaviour of components (Strogatz, 2003; Winfree, 2001; Kelso, 1995; Beek, Turvey, & Schmidt, 1992; Hollnagel & Woods, 2005).

Based on these basic assumptions, the models of human operators has developed from operator internal cognition (micro-cognition) to descriptions of the contextually guided adaptations the operator carries out to control the JCS' outcome (macro-cognition) (Hollnagel, & Woods, 2005; Hollnagel, 2006). The functional perspective of CSE also entails that the human operator is seen as an integrated part of the joint system. This change in focus means that the human operator is not given any particular privileges in the systems perspective since system performance is seen as an emergent process (Vicente, 1990). However, one has attempted to create macro-cognitive contextualized model the human operator to better understand the orderliness of human action.

Macro-cognitive models attempt to show how human performance can be explained by reference to contextual characteristics. These models are dynamic and contextualized in the sense that they attempt to show how a set of possible systemic consequences may arise from a given set of probable causes (Hollnagel, 1993), rather than attempting to make point-to-point estimations of human performance. These human performance models have shown how human control maintenance occurs on several control levels and time-scales simultaneously (e.g. the Extended Control Model; Hollnagel & Woods, 2005, p. 149ff). That the level of control an operator engages in is dependent upon the time available to perform control actions (e.g. the Contextual Control Model; Hollnagel, 1993; Hollnagel, & Woods, 2005), and that shifts in the operator's control level depend on the number of successful or failed actions performed on higher or lower control levels (Hollnagel, 1993). These models can predict the occurrence of categorical shifts in human control maintenance by showing how the operator's behaviour is dependent upon contextual and task-related characteristics. The human operator is in essence modelled as an adaptive and context sensitive controller who is an integrated part of the JCS.

The systemic perspective is according to Vicente (1990) particularly relevant for the investigation of correspondence-driven systems. Correspondence-driven systems are systems that are guided by external dynamic and goal-relevant constraints. In these types of systems the important task for the cognitive systems engineer is to find a way to present information to the user about the system's state so that the user can form a veridical understanding of the system (Vicente & Rasmussen, 1990).

However, as noted by Bjørkli (2007), this assumption is somewhat problematic. In situations where operators face unfamiliar or uncertain conditions for work, the operators'

performance becomes dependent upon reflection and understanding of the system's characteristics and not necessarily on the actual state of the system (Bjørkli, 2007). The presence of uncertainty is a vital characteristic of complex socio-technical systems (Vicente, 1999; Norros, 2004) and it is particularly so for transport systems (Burns & Hajdukiewicz, 2004; Bjørkli, 2007; Røed, 2007). This indicates that the operator's work in open, correspondence-driven systems, with large degrees of uncertainty, is dependent on both the operator's understanding of the system *and* of the representations of system states.

The implications of this insight is that it is one thing to model how the whole system achieves control, but it is an entirely different matter to model how the human operator achieves and maintains control over a process with uncertain dynamics. In other words, it is a difference between modelling the operator as an integrated part of the whole system and modelling the operator as a controller. Thus, it might be necessary to take an intermediate position between the modelling of internal characteristics of the human operators on one side, and the modelling of the JCS on the other.

**An Intermediate position between 'operator-centred' and 'system-centred' modelling**

It has been shown that the systemic approach have enabled an understanding of performance in human-technology systems that was not attainable using the componential approach (Dekker, 2002, 2004; Woods & Hollnagel, 2006). But, as mentioned above, the focus on the whole system performance where the operator is just an integrated part can be somewhat problematic. The problem becomes explicit when we observe the maintenance of control of open correspondence-driven systems affected by large amounts of uncertainty in system dynamics.

Uncertainty in the reception and production of variability. Uncertainty in correspondence-driven systems occurs when the effector systems' ability to bring about changes in system states are conditioned by contextual variance. An effector is a component of a system that responds to operator input and brings about changes in system states. In these systems it is a problem for the operator to know how control actions will affect system states (Petersen & Nielsen, 2001). This means that there is a form of discrepancy between the consequences the operator intended, and the action and the actual consequences of that action.

This differentiation between action and consequences have been thoroughly described by von Wright's (1971, p. 66ff) differentiation between *doing* and *bringing about*. This conceptual division is related to the difference between actions and consequences of action. The implications of this conceptualization for the understanding of effector systems in

sociotechnical systems have been described by Petersen (2004; Petersen & Nielsen, 2001). 'Doing' refers to the actions of a human operator who acts on the technical system in order to reach a given system state (Petersen, 2004). 'Bringing about' refers to the combination of an action and other events which contributes to the production of the consequence. This means that the consequences of all actions (whether human or technical) are conditional on the presence of other factors (von Wright, 1971).

Take the example of a car moving forwards at a speed of 50 km/h. If the driver starts to turn the steering wheel in a clockwise direction the car will steer towards the right. However, the action of turning the steering wheel clockwise is not in a determinate relationship to the car's rightward movement. It relies on a number of other factors that are conditional for this action to have this particular effect. For instance, the friction between the front wheels and the road surface must be above a given level, and the steering wheel must be connected to the front wheels. The principle is the same in all situations — any action must have a set of other conditions that allow that action to have a particular consequence (von Wright, 1971).

This principle becomes non-trivial when used to understand the operator's situation in correspondence-driven systems with a high degree of contextual variation. The consequences are great when the conditions that help actions 'bring about' intended consequences are not perceivable or at best uncertain (Bjørkli, 2007; Petersen, & Nielsen, 2001). The uncertain effect of the effector systems means that contextual variation not only creates unpredictable contextual variation, but also that the joint system's ability to handle these problems is uncertain.

This means that there is very difficult to help the operator produce a veridical model of the system, as expressed as a goal for cognitive systems engineers by Vicente and Rasmussen (1990). It is difficult because the actualization of the movement is not given in advance, but is an ongoing developmental trajectory that has different expressions depending on initial states, the operators' strategies and the physical forces that enable changes in the technical system's state. Since both sides of the 'equation' involving the level of disturbances and the ability to handle those disturbances are, at best, uncertain, the operator cannot be guided by contextual information alone (Bjørkli, 2007). This means that we must be able to model the ways that the operator handles this uncertainty. We must in other words describe the operator's understanding of the situation in an action-based format, and not in a system-state format. Thus, it might be a need to model the human-technology system as both a JCS *and* from the perspective of the operator.

A further problem for those who endorse *either* the systems view *or* the operator view is the way that the operator's actions are mediated by the technical system. Technical mediation refers to the way the technical system effectuates the operator's actions upon the controlled process.

The technical mediation of operator action. Human action is increasingly being subjected to a technical mediation, where the relation between actions and consequences are no longer directly mediated as it is in unaided human activity (Hoff, 2004; Øvergård & Hoff, 2005). The technical extension of the human perception or action ranges entails that humans can perform new sets of tasks more efficiently than was possible without the technical aid (Hancock & Chignell, 1995). However, this extension is not only positive, as the extension of human capabilities also entails that the technical component narrow down the number of possible ways actions can be performed. That is, technology alters the way that one can perform a task. The technical mediation also alters or removes parts of the experiences of performing an action (Heidegger, 1977; Ingold, 2000). This can lead to an experiential gap between operator actions and the consequences of these actions (Ihde, 2002; Øvergård & Hoff, 2005). The experiential gap that stems from technical mediation between human action and the consequences of these actions have relevance for the modelling of control maintenance in complex sociotechnical systems.

Hollnagel and Woods (2005) have talked about two different ways that an interface works when it connects a human operator with the controlled process. The first is where the operator interface allows the operator to work directly on the controlled process. This *embodiment-relation*, as termed by Hollnagel and Woods' (2005), exist when there is a tight coupling between the operator and the interface, often to such a degree that the operator acts *through* the interface, rather than acting *on* it to perform some task. The interface can be said to allow the operator a 'direct' but mediated view of the controlled process. In the second relation — termed the *hermeneutic relation* (ibid), the interface acts as an interpretative device which informs the operator about the state of the controlled process via the use of representations. The operator cannot use the interface to observe the controlled process, but must act on the basis of information that is translated by the technical system. This means that the operator must act *on* the technical interface in order to affect the controlled process.

Thus, on one hand there is the former categorisation of the relation between interface and operator where the interface acts as a facilitator for the operator's smooth unhindered coping with the controlled process (Wheeler, 2005). On the other hand, there is the latter categorisation where the technical system gives technically translated information regarding

the controlled process, but not allowing direct access to the controlled process. The interface thereby acts as a barrier to the smooth coping with the controlled process (ibid, Lützhöft, 2004). In this sense, we may understand the use of technical systems as a form of elaborate tool-use (Bjørkli, 2007).

However, the relation between operator and technical system does not always conform to these two types of categorizations. Technical systems and tools can shift from being things we can act through to obstacles to the operator's goal-directed activity. In other words, if the goal-directed performance is the analytical unit, one may find that the analytical unit relate to the human-technology system at one time, and to the operator at other times. This fluent nature of human-technology interaction can be described by the phenomenological observation that during skilled tool use, we do not perceive the tool as an independent object in the world, but rather as a something we experience the world through. In these situations the thinghood of the object recedes and the object becomes an extension of the user's body (see e.g. Merleau-Ponty, 1962, pp. 165ff). However, if the technical system for some reason does not work as planned, the interface retains its character as an 'object-in-the-world' that hinders smooth task performance (Lützhöft, 2004; Wheeler, 2005). The interface can in other words change character from being something the operator acts *through* to becoming a barrier for further activity. This change also alters the user's experience of the interface from being a medium for activity, to becoming an obstacle for the smooth coping (Hoff et al., 2002a, 2002b; Hoff, 2004).

This means that the JCS can in some situations become *disjoint*. This would happen in particular cases where the operators can no longer use technical system to intentionally alter system states. An example of this situation is given in Clark and Graybiel (1955; as cited in Holly and McCollum, 1996, p. 461).

> *The pilot took a waveoff as he attempted to land the helicopter on a spot lighted probably by four flashlights. Because of the extreme denseness of the fog he was unable to find the spot. As he circled to attempt a second landing apparently he became completely disoriented. While he was in a vertiginous state, he circled to the right but thought he was turning to the left. Although he was on instruments, he does not remember altitude or airspeed. As he crashed he stated he became a passenger and rode it in.*

When the operator can not make any control actions that alter system states the system is no longer a joint cognitive system, but becomes an uncontrolled technical system and a

helpless human operator. Then there is no joint cognitive system. This means that a model of the human-technology system should be able to model this transition or shift in system boundaries.

The modes of the technical mediation of the operator's action and the dual uncertainty of the actual contextual variance and the ability to handle this variance means that the operator some times must be understood on his own terms, since the situation may be perceptually underspecified or because the operator cannot understand the representations on the interface. The technical mediation of operator action and the presence of uncertainty regarding both the contextual disturbances that must be met, and the abilities the joint system will have to handle these problems are particularly present in the use of transport systems (Bjørkli, 2007; Burns & Hajdukiewicz, 2004; Petersen & Nielsen, 2001; Petersen, 2004).

**Transport systems as Joint Cognitive Systems**

The latest decades have seen an increase in the implementation of complex technology in the transport sector, thus increasing the complexity of the work domain. Thus, modern transport systems can be described as highly complex JCS which operates under a wide set of operational instructions, in highly variable contexts, and must meet several tasks at the same time (Burns & Hajdukiewicz, 2004). Modern transport systems fulfil all criteria that define complex sociotechnical systems[5] (see Vicente, 1999, p. 15ff). They have large problem spaces (Burns, & Hajdukiewicz, 2004) and they involve many human controllers who often have different cultural or educational background or are geographically distributed (Hutchins, 1995). There is a high degree of potential hazard related to the operation of transport systems (Perrow, 1998; Dekker, 2005), and many transport systems tend to have highly automated functions (Lützhöft, 2004; Sarter & Woods, 1995, 1997). Furthermore, transport systems are the archetype of dynamic systems that work in uncertain environments where contextual disturbances are the norm (e.g. Norros, 2004; Burns & Hajdukiewicz, 2004; Bjørkli, 2007).

The majority of human factors research have focussed on work in stationary process control plants, such as nuclear industry (Hollnagel & Woods, 1983/1999), process control (Vicente, 1999) or hospitals (Woods, & Hollnagel, 2006). The unfolding dynamics that must be controlled in stationary systems are connected to the physical characteristics of the controlled process. They can be described as more or less coherence-driven, closed systems which mean that the systems do not have external factors that affect the controlled process

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[5] Complex sociotechnical systems are a substitutable term for JSC.

(Vicente, 1990). Transport systems, on the other hand, are the archetype of open, correspondence-driven systems. Transport systems can also be said to be a *special* type of correspondence-driven systems, since they not only are subjected to contextual variance, but they also move around in the context of their operation, thereby leaving its own movement as the process to be controlled (Petersen & Nielsen, 2001; Bjørkli, 2007). This means that transport systems are not only exposed to contextual variability, but that the movement itself affects the contextual variability. For example, a car driving on a road is not only affected by the friction of the road, the visibility, or the presence of objects, but it can also alter it's relation to these objects by altering the way it moves on the road. By choosing driving speed the driver affects the available time to perform control actions and the friction needed to perform a turn without skidding (Fuller, 2000).

Contextual variation leads to a high degree of uncertainty regarding the ability to produce and control the movement of the JCS (Petersen, & Nielsen, 2001). The contextual variability does not only affect the external disturbances that the transport system must handle, but it also affects the ability to meet these disturbances (Petersen, 2004; Petersen & Nielsen, 2001). This means that transport systems engender challenges to efficient production that are different from what we find in towards stationary JCS (Burns & Hajdukiewicz, 2004, Bjørkli, 2007).

Furthermore, transport systems allow for a particular mediation of human activity. It not only allows for movement in new context, butt the activity itself alters the position and perspective the operator has. This coupling of transport system movement and self-movement entails that the operators in many situations extends their perception of action possibilities to also include their vehicle. This is supported by experimental evidence that indicate that experienced drivers of a wide range of vehicles in some way extends the perception of passable apertures to also cover the vehicle that they control (see Shaw, Flascher & Kadar, 1995, for a theoretical and empirical review). This close connection between experienced operator's and their work domains has been empirically noted before, particularly in supervisory process control (metal manufacturing industry; Norros, 2004) In this sense, the transport systems form a functional and experiential unit with the operator. A movement of the steering wheel of the car not only affects the car's movements but also the driver's movement. In this sense is movement with transport systems just a different mode of making self-movements. The vehicle becomes something the operator uses to produce self-movement; hence the relation between the vehicle and operator becomes a type of embodiment-relation (see Hollnagel & Woods, 2005, for a description of the embodiment-relation). The

experiential mode of interacting with the technical systems is believed to affect human work with technical systems (Hoff et al., 2002a, 2002b; Hoff & Øvergård, In press).

Because the controlled process in transport systems are dependent upon the physical forces that act upon the technical effector systems, they are inherently dependent upon contextual variation to perform their tasks. This dependency upon the interaction between the technical system and the variable environmental state means that the capability of bringing about changes in movement is highly dependent upon environmental factors.

This uncertainty of the capability of bringing about system changes is particularly descriptive of marine transport systems (Petersen, 2004; Petersen, & Nielsen, 2001). This gives rise to new sets of problems that must be addressed by human factors researchers. The question becomes how an operator handles the uncertainty in the ability to effectively meet disturbances. When the effect of control actions is not predicable in advance it must in some way be tackled by an adaptive feedback controller (whether human or technical). To understand how these events affect performance, we must understand how the operator deals with this uncertainty. This means that the observations of transport systems might be a possible field of investigation where one might observe the dual nature of human-technology systems where operator's acts both as an integrated system, but where uncertainty and the mediation of action also entail that the operator some times must be modelled as a distinct part of the system.

**Research focus**

This thesis takes as its starting point the challenge of understanding the basis for human operators' goal directed interaction with technical systems (all articles). It questions how technical systems and design recommendations set the premises for human goal-directed activity (Article I & II) and does so particularly by focussing on how humans achieve and maintain control over moving JCS (Article II, III & IV).

The thesis involves a re-framing of human interaction with technical systems. The thesis starts out with a test of how different interface designs affect human performance in an experimentally constrained but goal-directed task (Article I). It then moves on to presenting a theoretical reframing of the nature of human interaction with the environment, and describes three phenomenological aspects that are of particular importance when it comes to describing the experiential aspects of human control over technically aided movement (Article II). The last two articles seek to broaden the conceptual understanding of military High-Speed Crafts in confined waters. The focus in these two articles is on the control strategies and models used by the navigators (Article III & IV).

The works presented in the thesis have attempted to maintain a close connection between the models that we use to interpret human behaviour, the work domains we observe operators' performance, and the actual interpretation and modelling of that performance.

**Methods**

I have kept the articles in the same chronological order as they were written. This has been done so to present the historical development of this research project. Concepts and terms used differ somewhat between the articles. This discrepancy has been deliberately kept intact in order to show the conceptual and theoretical development during the project.

This thesis combines several methods and approaches to the understanding of the relationship between the human operator and technical work domains. The choice of a combination of different approaches is based on the arguments of Vicente (1997), i.e. that human factors researchers should triangulate between highly controlled laboratory experiments, less controlled experiments, simulator-based experiments and real-world qualitative investigations of the phenomenon in question. Each of these levels of scientific investigation involves different methods as the methods one use must be adapted to the research object. Experimental (article I), theoretical and philosophical (article II) and observational studies using video camera and interviews (articles III and IV) are included in this thesis.

The first article presents first a highly controlled laboratory experiment (article I) which investigates the effect of ergonomics recommendations for interface design on human performance. The method and related problems is thoroughly described in the article. The second article presents a triangulation of theoretical and philosophical arguments based upon empirical approach to how one can conceptualize the human operator as an extended controller of action. The other empirical articles (article III and IV) present the use of video camera to record incidents and conversations during the real-life high-speed navigation and manoeuvring. The observations and transcriptions were validated through agreement between the authors of the articles.

All the included works have had the aim to increase the understanding of the effect of technical work domains and of constructed environments (both simulated and real) on the human operator. These approaches have followed the same underlying conceptual framework, - namely that of cognitive systems engineering. However, the individual scientific works have not focussed on any particular methods as the highly complex and multidimensional nature of human work and performance in complex technical environments need a wide set of approaches to be fully understood (Vicente, 1997). Each research object has been approached in the way that seemingly could best answer the problem at hand.

## Articles Included in This Thesis


**Article I**

Øvergård, K. I., Fostervold, K. I., Bjelland, H. V., & Hoff, T. (2007). Knobology in use: An experimental evaluation of ergonomics recommendations. *Ergonomics*, 50(5), 694-705.


The aim of the article was to test a set of ergonomics recommendations to see how operator performance was affected by interfaces that either followed or did not follow ergonomics recommendations presented in a well-used ergonomics textbook (Kroemer & Grandjean, 1997). Ergonomics standards may be viewed as a set of models of a population of users. These standards (Department of Defence, 1999) and textbook recommendations (Kroemer & Grandjean, 1997; Pheasant, & Haslegrave, 2006) works as a basis for interface design. The standards are described in such a way that it does not account for environmental or task variance or cognitive differences among operators. Ergonomics standards such as the military standards in the American military (Department of Defence, 1999) or the ergonomics recommendations given in various textbooks (e.g. Kroemer & Grandjean, 1997; Pheasant & Haslegrave, 2006) can be seen as examples of static standards or design norms. We investigated the importance of ergonomics standards for human performance in an experimental task involving goal-oriented action.

The results indicate that performance is not univocally better when interface design conformed to the ergonomics recommendations as opposed when the interface design was not according to the ergonomics recommendations. The results of this article imply that even simple and experimentally constrained goal-directed tasks are dependable on several sets of constraints related to the task, the operator, and the relation between these constraints. Additionally, the results indicate that tasks used to test motor memory (within the information-processing approach; Wilberg & Adam, 1985) were affected by a wider set of constraints than those acknowledged by information processing theory (Magill, 1982; Goodman, 1985; see Article II; Øvergård et al., 2007, p. 703 for the specific argument). In effect these results indicate a need for a dynamic model for human performance that acknowledges the different levels of constraint present in interaction between operator and interfaces.

**Article II**

Øvergård, K. I., Bjørkli, C. A., & Hoff, T. (2008). The bodily basis of control in technically aided movement. In S. Bergmann, T. Hoff and T. Sager (Eds.), *Spaces of Mobility* (pp. 101-123). London, UK: Equinox Publishing.

The article describes an explicit theoretical and philosophical basis for the understanding of human operators who work with technical systems. The article starts out with pointing out the increased use of technically aided movement in the world. The use of technical systems for mobility purposes greatly increases efficiency but it also leads to accidents and pollution which causes numerous injuries and deaths each year. Reports have argued that human error could account for as much as 90 percent of these accidents. However, these reports are built on the assumption that humans and technical systems are physically and functionally separate in relation to the outcome of the joint human-technology system's behaviour. This means that humans are blamed for accidents as long as the technical component has worked properly (Dekker, 2002, 2004). In this view, the technical system becomes a neutral physical object which people use purposefully.

However, this 'neutral' view of technical systems is problematic as it has been shown that the mere availability of information and action possibilities are not enough, but this information must also be perceivable by the human operator (Woods, et al., 2002). Thus, we must acknowledge that technical systems should be designed by focussing on observers-dependent measures, as opposed to objective observer-independent measures (Flach, 1995). The article proceeds with this perspective in mind and further draws upon the embodied mind approach which posits that human interaction with the environment are fundamentally based upon a reciprocal coordination between human minds, bodies and environments (Clark, 1997). Movement and action then becomes ontologically prior to cognition because the perceptions and actions founds the basis for any categorization (Ihde, 1983). This understanding supplants the componential view of humans and technology with an *embodied-mind paradigm* (Clark, 1997) that acknowledge the interdependency between humans and the environments (and technical systems).

The article presents three phenomenological characteristics, derived from empirical and philosophical research, which arguably describe human use of technical systems and tools. These arguments show that human interaction with natural or technical environments is based upon goal-directed perception-action cycles. The change from unaided bodily

movement to technically aided movement leads to an *extension* of human cognition and action capabilities (named extension of the body) into and through the technical system. Technical systems in essence *mediate* human action. This technical extension or mediation often exceeds the action capabilities for the unaided human body, and thus shifts the constraints for possible action into the relation between technology and environment, rather than between humans and the environment (Øvergård & Hoff, 2005). The shift in constraints of the controlled process creates a possible experiential gap between the actions performed by the human and the consequences of these actions (Hoff et al., 2002a, 2002b).

With these phenomenological characteristics of human interaction and use of technical systems in mind, the article then turns to asking how technical transport systems affects the human ability to control the movement with the vehicle. The problem of technical over-extension of human bodily perception-action capabilities is a possible source of alienating the human operator to the process s/he is supposed to control. These aspects points to the need for a time-dependent and interaction-based approach to human-technology interaction that can account for the fluent, dynamic relationship between the operator and the technical system.

**Article III**

Bjørkli, C. A., Øvergård, K. I., Røed, B. K., & Hoff, T. (2007). Control situations in high-speed craft operation. *Cognition, Technology, and Work*, 9, 67-80.

The article investigated the control strategies that military navigators used when manoeuvring high-speed crafts in confined waters. It was based upon the conceptual framework called the 'control situation framework' presented by Petersen (2004). This framework posits that control maintenance can be generically described as the relation between the *control possibilities*, and the *control requirements*. Earlier approaches have generally evaluated performance according to system states and how this state is in relation to system goals. However, Petersen makes the argument that the performance of context sensitive systems faced with dynamic situations and uncertainty cannot be evaluated from the specification of systems states. It must rather be evaluated according to how the control situation is affected by the change in control possibilities or control requirements because the ability of effector systems to bring about changes in system states is dependent on contextual circumstances (Petersen & Nielsen, 2001; von Wright, 1971). Transport systems are known

for the dependency on contextual variance (Burns & Hajdukiewicz, 2004), and this differentiates transport systems from other stationary supervisory systems (Bjørkli, 2007).

Marine navigators are continually faced with the necessity to balance demands for safety and efficiency. The demands are made concrete by organizational demands for fast movement and the need to maintain the functional integrity of the vessel by avoiding collisions with objects and rocks during the navigation. The navigators achieve the goals of efficient navigation by sailing as fast as possible (often at top speeds), while they achieve safe navigation by either stopping (reducing speed) or steering away from dangers. Thus the navigators are faced with two primary ways of controlling the vessel's movement, either by controlling speed or through the control of heading. These control actions jointly affects the present and future control possibilities and control demands at any given time.

The article observed how navigators chose to balance these demands and possibilities for control during manoeuvring in confined waters. The balancing between the demands and possibilities of the situation was observed in situations where the navigators chose a trajectory that went closer to the nearby dangers (e.g. sunken rocks) than necessary, but that enables easier handling of future actions. This reflects a strategy of *control optimization* by pushing the borders for safe manoeuvring by not maximizing distance to dangers, but rather to exploit the available space to improve the ship's future position. This strategy can be compared by a situation where the navigator *idealizes control* at all times by maintaining the maximal distance to near-by dangers. This control idealization can be compared with Gibson and Crooks' (1938) notion of "Field of safe travel". In a static system-state perspective is this way of controlling the vessel superior to the optimization-strategy since it at any point in time have a larger distance from dangers. But when seen in a dynamical time-dependent view, the optimalization strategy is superior; because it takes into account both the vessel's movement dynamics and upcoming dangers. Further, the navigators can alter the balance between control possibilities and control demands through setting the speed for a particular region, - thereby specifying the range of demand and possibilities that exist in a given region.

The findings indicated that in addition to acknowledging the unfolding interaction between control possibilities and control requirements one should also focus on the *control strategies* the navigator used to maintain acceptable control.

**Article IV**

Øvergård, K. I., Bjørkli, C. A., & Hoff, T. (In review). Models and Control Strategies used by Experienced Marine Navigators. *Cognition, Technology, and Work.*


This article further extends the control situation framework by testing how this framework could be used to describe the model's the operators had of the controlled system. Any dynamical model of a human-technology systems should be able to describe "the models the users may have" (Hollnagel, 1993, p. 377), meaning that it should reflect an authentic phenomenological description of operator's perspective. This description must involve an operator-dependent model of the system and the environment that can account for the real-life adaptations an operator makes. The reported data was taken from two series of events.

The first (the, 'Kjøtta incident') involves observations of the adaptations performed by the navigational crew in order to re-establish knowledge of their actual position. Lack of exact position was a problem for the crew because the ship was bounded into a narrow straight that contained several sunken rocks. The visibility was poor due to night-time and occasional snow and rain showers. Hence, the navigator had to navigate using only beacons because perches and landmarks were not visible in the darkness. The beacon was not seen at the expected time, thus indicating that the crew did not have an exact estimation of the ship's position. The crew made several adaptations of the ship's movement capabilities to meet control requirements that were uncertain due to the lack of an exact knowledge of the ship's position. The navigator first lowered the speed to relieve time pressure, secondly he increased the gain on the ship's rudder control so large rudder angle changes could be made quickly on demand.

The second series of events (the 'Indre Folda reflections') involve transcriptions of verbal reflections on four occasions between the commanding officer (CO) and the navigator aimed at improving manoeuvring in confined areas. The reflections were related to the planning and optimization of passage narrow passages, and to strategies for making small changes in heading during manoeuvring in narrow passages. Manoeuvring with marine vessels involve uncertainty due to the influence of contextual disturbances on the ability to bring about changes in system states (Petersen, 2004). This means that the operators must adapt not only to the contextual disturbances, but also to the uncertainty of being able to adapt to the control requirements.

The results from the two sets of observations relate to the adaptations made in response to the uncertainty of both control requirements and control possibilities. The results

across all observed conditions indicated that the operators adapted to uncertain situations by increasing the control possibilities and reducing the control requirement related to future adaptations on short time-scales. Further, effective control demands that operators take into consideration the specific expression of the ship's turning capabilities. The data indicated that the operators adapted exactly in order to meet these physical constraints.

The strategies of preparing the joint system for control actions made on short time scales can be understood as a function of the navigators' model of the situation and the situation in itself: Firstly, high speed craft manoeuvring is first and foremost guided by the constraints set by the immediate environment. The environmental constraints also directly affect the time constraints that navigators have to perform control actions. Secondly, the capability of the craft's effector systems to bring about system state changes is conditional upon other contextual factors such as wind, currents and waves. These contextual factors are not readily perceived by the human operator and thus create uncertainty of the actual capability of the craft's effector systems (Petersen, 2004). By reducing the need to make quick adaptations on shorter time scales the operators give themselves more time to deal with unanticipated changes in the craft's movement dynamics.

The results indicate that the concepts of control possibilities and control requirements reflect basic aspects of the navigators' control strategies and models of the work domain. The observations of the navigating crew's strategies and verbalizations during the Kjøtta incident indicated that they explicitly balanced control possibilities up against control requirements. The reflections at Indre Folda also indicated that these strategies were guided by an explicit knowledge of the how the physical and temporal dynamics were *actualized in manoeuvring*. This means that navigators' model is rather based on the *functional expression* of the interaction between hydrodynamics and effector systems, rather than being a formalized specification of the characteristics of the effector systems as such.

**Reflections**

The modelling of human-technology systems have gone through the increase in the analytic unit from single components that interact to more systemic approaches involving the co-agency between operators, technology and environment (Hollnagel & Woods, 2005). The increase in the analytic unit has allowed us to see connections in human-technology system performance that was not visible before (Dekker, 2005).

Hollnagel and Woods (2005, p. 49) states that " *... the purpose of science is to produce valid, scientific knowledge about a particular domain or problem area"*. This thesis adheres to that understanding of science. It has both *investigated* (Articles II – IV), and *tested* (Articles I, III & IV) ways of modelling the human operator's interaction or co-agency with technical systems.

I would claim that this thesis has at least two possible implications for the modelling of the human operator. The first implication is the possibility of modelling the human operator as an extended controller. The second implications is that one should consider to model the human operator both as a separate and as an integrated part of the system, rather than only modelling the human operator as a part of a larger system. The following sections discuss these to implications in more detail.

The human operator is an extended controller. The articles (III & IV) have expanded the control situation framework to cover not only the formal description of the control possibilities and control requirements for a given system (Petersen, 2004), but suggest that this way of describing operator control maintenance in uncertain environments also should include descriptions of the operator's control strategies (Article III). Furthermore, it has also been shown how the control situation framework can also be used to describe the operator's models of the work domain (Article IV). The operator's models are based upon an understanding of the functional expression of the interaction between the ship's effector systems (rudder, propellers and hull) and hydrodynamics. Together with fact that navigators can estimate a ship's future position, this understanding of the operator's models indicate that marine navigators are oriented towards dynamic change rather than the passive maintenance of system states. This points an important argument in the control situation framework, namely that both control possibilities and control requirements are based upon an active sense of controlling. Control possibilities relate to *what the operator can do*, i.e. what effective actions that are available for altering system states. Similarly, control requirements refer to *what must be done* to maintain the human-technology system within acceptable operational boundaries (Petersen, 2004; Article III). The perspective is based upon understanding the

activity as it unfolds, rather than static estimations of the transition between discrete system states. The active understanding of the human operator's control maintenance resonate with the second article (Article II) that points to a bodily and cognitive extension of the human mind (or operator). The joint goal-directed activity unites humans and technical systems (see e.g. Maravita et al., 2002; Berti & Frasinetti, 2000; Merleau-Ponty, 1962, p. 165). The human operator becomes not just an operator of a technical system, but an *extended controller* of that system, which must internalize the systems dynamics or extend and adapt the perception-action cycles to include the system's physical boundaries (see e.g. Shaw et al., 1995, for a theoretical review of the extension of perception and action).

<u>Modelling the operator as both separated and integrated with the technical system</u> The second implication of this thesis is that marine navigators extend their perception-action cycles to cover the transport system's functional and physical boundaries. Combined with the observation of the operators control strategies as used in uncertain situations, there is reason to ask whether the operators should be modelled on its own right, rather than being modelled simply as an integrated part of the whole system.

The integration of the user in the technical system leads to a methodological challenge by creating a situation where an intentional component becomes a part of a larger system that can be said to have intentions and goal of its own. According to the systems approach to human-technology systems, the human operator is only a part of the system, and is not given particular importance on its own (Vicente, 1990). However, as presented in Article III and IV the human controller in marine navigation is surrounded by uncertainty arising from contextual disturbances, and uncertainty concerning the ability to bring about changes in system states. This brings forth the challenge of making models that show how the human operator is *both* an intentional component *and* a part of the larger system. To describe this duality (but not dualism) of human-technology systems, we need to articulate the basis for this dual nature of human-technology co-agency. One way of analyzing context-bound phenomena or open systems has been described by Jaan Valsiner as *inclusive separation*:

> The second way to separate a phenomenon from its context is by *inclusive separation:* The target is differentiated from its context, but the context is retained in the subsequent analysis because it is considered to be interdependent with the phenomenon. Although the emphasis in research is on the object phenomenon, the relevance of the context is recognized in the investigation.
> (Valsiner, 1997, p. 24, Italics in original).

This way of analyzing the human operator means that we can describe the human operator in a way that still maintains the individuality of the operator while also showing how the operator is integrated within the larger system. This approach would be a middle course between "OPERATOR-only" models, which describe the operator as a de-contextualized closed system and "SYSTEM-only" models, which describe the output of the whole system while ignoring the behaviour of the system's components.

This argument of creating an understanding (or model) that shows the inclusive separation of the operator is strengthened by the fact that the borders between a system and an operator can be fluent. If the analytical unit is aimed at the intentional goal-directed behaviour, then the unit may at some points in time relate to the human-technology system and at other times at only the human operator. This fluent nature of human-technology interaction can be described by the phenomenological observation that during tool use we do not perceive the tool as an independent object in the world, but rather as extensions of our bodies or minds (Clark, 1997, 2003, 2005). This extension of the human operator, which happens both with tools (Maravita et al., 2002; Merleau-Ponty, 1962, p. 165; ) and transport systems (Shaw, et al., 1995) would be difficult to model and understand in the systemic approach, where the operator is 'merely' a part of the system. It has been proposed that cognitive systems engineers should attempt to design for the establishment of the embodiment relation (Hollnagel & Woods, 2005). Other researchers have gone further and argued that the mediation of action and the embodiment of tools and technology should be a research focus with the aim of producing technical systems that are easier to use (Clark, 2003; Hirose, 2002).

I find, at least in relation to the work domains observed in this thesis, that there is a firm theoretical and empirical basis to question whether one should model the relation between the operator and the technical system on its own. My approach to this problem is that we should not model the human operator as integrated into the physical system as such, but rather that we should allow for *the models of the human operators* to be integrated with *the models of the technical system*. We must in other words be able to separate the operator's personal perspective from the objective 'birds-eye-view' of the whole system.

At first glance this might seem like a tall order. However, I believe that the activity-based framework for understanding the operator already simplifies the integration of operator models with system models. By viewing the operator as an extended controller that temporarily can transcend the boundaries between body, technology and environment, we have already implicitly said that the human operator is not only the operator's cognition and body, but that the operator is extended both cognitively (Clark, 1997, 2005) and bodily

(Maravita et al., 2002; Merleau-Ponty, 1962, p. 165; Hirose, 2002) into the surrounding technical or natural environment. This means that the model of the operator must involve these objects that extend the operator's ability to act ― not as external objects as such, but rather as objects that are perceived and acted on.

So what does this imply for the modelling human operators? This thesis presents arguments for modelling the operator by emphasising the aspects of the work domain that the operator can perceive. In other words, we should only include information that is available to the operator. This means that the extended user model must have a type of *phenomenological validity* that reflects the operator's experience and perspective. It is of no use to include aspects of the technical system that are not available to the human operator (if it did it would not be called an operator model). The modelling of the technical system should on the other hand describe the objective situation, including aspects of the technical system that are not available to the operator in any sense (e.g. the actual physical state of effector systems, the internal workings of automation systems etc.) but that still can give insights into how the JCS perform.

This thesis aims to contribute to the development of CSE research. I believe we can acknowledge the relationship between humans and technology that affects human work, without leaving the goal of the CSE-tradition. To the extent this thesis succeeds – it should be measured to how it would help us to understand and predict how whole human-technology systems create efficient, safe, sustainable and healthy human-technology systems.

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# Models and Control Strategies Used by Experienced Marine Navigators

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**Abstract**

Dynamic models of complex sociotechnical systems must describe the operators' model of
the work domain. This paper tests whether the Control Situation Framework is suitable for
describing the models marine navigators use to guide high-speed crafts through the
Norwegian archipelago. The reported data are from two series of events. The first involves
observations of the actions taken by the crew as to re-establish their actual position. The
second series of events are transcriptions of the verbal reflections between the chief and the
navigator aimed towards improving manoeuvring in confined waters. The results indicate that
the navigators adapt to the interrelation between control possibilities and control
requirements. The navigators were guided by explicit knowledge of the functional
characteristics of psychical and temporal dynamics which were actualized in manoeuvring.
This indicates that the control situation framework can be used to describe the models the
operators use.

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# 1. Introduction

The modelling of complex sociotechnical systems that are subject to large operational and environmental variation is a complex task. In fact, researchers within the Human Factors discipline by and large agree that naturally occurring human behaviour in complex sosiotechnical systems is so variable that it cannot be predicted with any reliable accuracy (Hollnagel & Woods, 2005; Hollnagel, 1993; Burns & Hajdukiewicz, 2004). The alternative to exact predictions of operator behaviour is to focus on how human work performance is initiated by contextual circumstances (Hollnagel, 2005), or on categories of events that are found to be associated with the loss of control (e.g. Sarter & Woods, 1995, 1997; Woods & Hollnagel, 2006). The focus has in this sense shifted towards creating dynamic models that shows how a set of possible consequences may arise from a given set of probable causes. This modelling implies that we must use models that have an affinity to the time-dependent development of the sociotechnical system (Hollnagel, 2002).

Hollnagel (1993) and Cacciabue (1996) have put forth three requirements that models of human-technology interaction must fulfil. The first requirement is the need for the model to reflect the system's historical development, even though this is not directly observed at "present-state" observations. The second requirement is that one should not only describe the system as it is externally observed, but the model must also be able to describe "the model the user may have" (Hollnagel, 1993, p. 377). This suggests that the system model should somehow contain an abstraction that reflects the operator's model of the whole system. We understand the notion of "the user's model" in the sense that it should reflect an authentic phenomenological description of the operator's perspective involving the relation between the user, the system and the environment (see Norros, 2004 for a similar approach). The third requirement stated by Hollnagel (1993) is that the system model should take into account the cooperation between multiple people and artefacts that constitute the context for control maintenance.

Hollnagel (1993) and Cacciabue (1996) argues that modelling must account for all factors which play a significant role in the control of human-technology systems, and that specific models do so to the extent that these three modelling requirements are attended to. It is a particular challenge for dynamic operator models to show how human operators translate system variance into parameters in a way that allow effective control. This approach implies

something quite different from the modelling of variance per se, as it aims to show how operators exploit the system's ability to produce variance in order to reach system goals (Hollnagel & Woods, 2005). We have previously shown that the control situation framework (Petersen, 2004) can be used to make sense of joint system adaptation to unexpected changes in control requirements (Bjørkli et al., 2007). The following section shortly outlines the control situation framework as presented by Petersen (2002, 2004; Petersen & Nielsen, 2001) and Bjørkli, Øvergård, Røed, and Hoff (2007).

## 1.1. The Control Situations Framework

The control situation framework focuses on the operators' ability to *control* system performance under variable conditions. It starts out with the notion of *the control situation* which can be described as the ability to use *control possibilities* in order to meet current and future *control requirements*. Control possibilities refer to the potential the joint system have for bringing about system state changes. For example, a ship's ability to turn is dependent on both the design of the hull and rudder system and the given water flow. The ability of the marine navigator to initiate a turn is thus a function of the availability of relevant input devices (i.e. steering wheel) and of the effector system's ability to bring about system state changes (Petersen, 2004; Petersen & Nielsen, 2001). Control requirements, on the other hand, can be described as "the requirements for bringing about appropriate state changes in the controlled system" (Petersen, 2004, p. 266). Control requirements are not formal descriptions of specific system states, but rather the formulation of *the ability to bring about* state changes that fits with the system's goals as they are expressed in particular situations. This implies that the focus is on the operator's ability to change system states and not on the system states as such (Bjørkli et al., 2007).

The control situation framework further points to the operator's ability to maintain the joint system within the *acceptable action spaces*, by adapting to control requirements in such a way that it satisfy both safe and efficient manoeuvring (Bjørkli et al., 2007). Acceptable action spaces refer first to the actualization of current control possibilities to meet control requirements, and second to the degree that the control actions effectuated at one point in time are coherent with the future maintenance of goal states. These two considerations can be described by the difference between the *idealization* and the *optimalization* of control. Manoeuvring in confined and demanding waters is a matter of adapting to the *future* control demands through the optimalization, rather than idealization, of control (Bjørkli et al., 2007).

The idealization of control relates to the maintenance of a maximum distance from "here and now" dangers, which implies that the navigator chooses to always put the craft in the middle of the safe waters. This approach to navigation and manoeuvring is somewhat similar to Gibson and Crook's (1938) "Field of Safe Travel" where it is presupposed that drivers attempt to "…*keep the car headed into the middle of the field of safe travel*" (Gibson & Crooks, 1938, p. 456, italics in original). The idealization of control entails that the operator keeps the maximum possible distance away from obstacles. Any manoeuvring that is based on the idealization of control will then relate mainly to the present and immediate terrain and control requirements.

The optimalization of control, on the other hand, seeks to balance the demands and possibilities for control in order to achieve *both* safe and efficient movement. This implies that the transport system in question sometimes reduce its distance from dangers in order to obtain a position that improves the ability to navigate safely and efficiently in future trajectories. The system (e.g. a ship or a car) moves out from the centre of the field of safe travel and sometimes stray close to some obstacles in order to improve the conditions for future manoeuvring (e.g. the next turn). The optimalization of control mode is a clear example of how the joint system creates both the demands and the possibilities for control (Bjørkli et al., 2007).

The control situation framework has been used to describe and explicate both particular work domains as well as theoretical modelling problems. The relevance of the control situations framework for the dynamic modelling of the system have up to today been related to the following aspects; a) description of actual control actions that was effectuated as adaptations to unanticipated events (Bjørkli et al., 2007), b) the description of the interdependence between effector systems and the operative environment (Petersen, 2004), and, c) pointing out that abstracted representations of means-end systems must include the physical realization of the means systems (Petersen & Nielsen, 2001). These articles show how the control situations framework can be used to cover the first and third of Hollnagel's three requirements to dynamic models of man-machine interaction by showing how disturbance in system states are met by the interplay between operators, artefacts and effector systems (Bjørkli et al., 2007). However, there has been no discussion as to whether this framework can accommodate the operator's model of the situation.

### 1.2. The aim of this article

This article addresses the question whether it is possible to include the operator's models of the system in the control situation framework. We have previously shown how the navigator's adaptation to non-predicted disturbances or threats to system integrity is describable by the control situation framework (Bjørkli et al., 2007). The fact that observed operator behaviour can be categorized within a given conceptual or theoretical framework, however, does not entail that that framework is a good representation of the operator's actual work. The focus of any conceptual framework or model must be to capture the underlying process that identifies the core of the phenomenon in question (see e.g. Norros, 2004). Thus, a model of human work domains must have authenticity, meaning that it must be based on actual and authentic observations of work practises (Woods, & Hollnagel, 2006). We will present transcriptions from verbal reflections made by military navigators during high-speed craft navigation and manoeuvring in complicated situations. The aim is to see how the operator's models of the system are expressed in the verbal communication between the navigational crew.

### 2. Method

The basis for this study is the participation in, and observation of, different navigation teams during three naval exercises in the Norwegian Royal Navy in the period between 2003 and 2005. Observational data was gathered by observation of the crew on the ship bridge engaged in navigation and manoeuvring of military High-Speed Crafts (HSC). All observations was videotaped by one stationary camera and one hand held camera. The stationary camera provided an overview over the ship bridge, and the handheld camera was directed at concrete actions of the crewmembers, as well as interface details. The two video streams were synchronized to provide multiple perspectives of the crew activities during performance. In total 120 hours of video was gathered in diverse operational settings over the project period 2003 to late 2005.

### 2.1. Hauk Class Vessels

The Hauk-class vessels are a category of ships in use in the Norwegian Royal Navy for patrolling and operating in inshore waters. The Hauk class sails under the formal instruction of upholding national presence along the coastline of Norway in an efficient and safe manner. Safety is defined as the maintenance of the functional integrity of the ship and crew enabling

a continuous ability to respond to orders given by the military authorities. Efficiency entails the ability to patrol large areas by holding high speeds while maintaining safety. The practical realization of these formal instructions involve that the crew and vessel must have the capacity to handle a wide range of maritime environments such as open or very confined waters, and to sail during any time of day/night and in any weather conditions.

The Hauk vessels are categorised as fast patrol boats. The vessels is approximately 36,5 meters with a beam of 6,5 meters, a displacement of 150 tonnes, and capable of operation speeds of approximately 32 knots (17 meters per second / 60 km/hour). The Hauk Class is specifically designed for keeping high speeds combined with maintaining good steering capacities – a combination crucial for operation in very narrow in-shore waters. Figure 1 shows a Hauk class vessel.

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Please insert Figure 1 about here

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## 2.2. Crew Organisation

Five persons of the total crew aboard are directly involved in the navigation. The *navigator* has the responsibility of safe and efficient operation of the ship. The navigator prepares the courses to sail before departure and executes this plan during operation. The *plotter* supports the navigator during operation by handling the chart and contributing to determination of ship position. The plotter exchanges information about navigation calculations with the navigator. The chart desk and plotter is placed behind the navigator. The *helmsman* steers the ship by using a wheel in accordance to verbally ordered courses by the navigator. The *lookout* is positioned at the top bridge outside the interior ship bridge and reports to the navigator what he visually observes in the environment that might be relevant for navigation safety. The last person directly involved in the ship navigation and manoeuvring is the *commanding officer* (CO) of the ship that bears the overall responsibility for the safety of the ship. The CO is responsible for solving the military and strategic tasks carried out. The commanding officer usually supervises the navigator when involved in the navigation.

The individuals on the navigation team have their assigned workplace on the bridge as indicated in figure 2:

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## 2.3. The Manoeuvring Capabilities of the Hauk Class

The maneuvering capabilities of the Hauk-Class have been thoroughly described in previous publications (Bjørkli et al., 2007), but we will briefly outline the important aspects of the ship maneuvering capabilities.

The Hauk-class uses a twin rudder system for maintenance and change of course. Course stability and change are effectuated through hydrodynamic principles that specify the interaction between the water flow along the hull and angle of the rudder. The water flow along the hull of a ship with symmetrical sides and the rudder amidships in calm waters refers to a symmetrical flow. Any athwartship forces exerted are balanced and reciprocally evened out. In this balance of longitudinal and athwartship forces, the ship maintains a straight-line course.

In order to change course, the navigator changes the balance of forces and initiates a rotational movement. The rotational movement in a turn unfolds in three distinct phases. The first phase is initiated by the turning of the rudder. The change in rudder angle produces a minor lateral force that heels the ship slightly inward in the early phase of a turn. This movement results in a change in water flow in the bow, where the water now pushes more on one side of the hull. The second phase starts as the ship begins the rotational movement, where the ship heels outwards in the turn as this process is initiated immediate after the change of rudder angle. The third phase starts when the angular rotation speed is constant around the vertical axis in a steady turn where the lateral forces and the water flow acting on the bow are in balance. The rudder pushes the ship sideways into the water flow, resulting in the lateral force in a turn.

The three phases making up a full turn of the Hauk-Class are initiated in a sequential process. The phases and their order of occurrence are determined by the relation between the hydrodynamic forces that act upon the hull and rudder system. These forces and the sequential nature of the turning phases are absolute physical constraints that the navigator must take into

consideration when maneuvering in confined waters (Bjørkli et al., 2007; see also Petersen & Nielsen, 2001). Maneuvering in narrow passages becomes a challenging task since the three phases evolves in a non-linear fashion which is conditional upon unpredictable contextual variation such as waves, currents and wind. This means that the vessel's actual turning capabilities can be highly variable. The main challenges are instantiated in the anticipation of the on-set and expression of each phase of a turn.

## 3. Results: Observations and Transcriptions

This article reports observational data obtained under two different series of events related to marine navigation and manoeuvring, respectively termed "The Kjøtta Incident" and the "Indre Folda Incidents" (Both named after the geographical name of the place where the incidents occurred). Each of these operational settings offered different challenges for the ship and crew. The main tasks related to different aspects of the relationship between navigation and manoeuvring necessary to sustain the joint system's functional integrity.

The Kjøtta Incident (paragraph 3.1.) refers to a critical event that occurred during a military exercise in November 2003 in the archipelago north of the Norwegian city Harstad. The event took place just outside the small island Kjøtta, and included an escalation of stress factors for the crew due to accumulated uncertainty in ship position, temporary crew structure, and technical malfunctioning.

The second set of observations stems from video recordings of HSC operation in confined waters during a military exercise held at Indre Folda at the coast of Norway (paragraph 3.3). This is a region known for its demanding and confined waters, where the ship and crew are pushed towards the limits of their capabilities. Four verbal reflections made by the crew aboard the HSC taken from the Indre Folda navigation exercise are reported.

### 3.1. The Kjøtta Incident: Navigating under uncertainty

The incident took place on the 18th of November 2003, 01:13 AM under poor visual conditions with fog and occasional snow and rain showers. The time code in the transcript is relative to the recorded incident (00:00 to 16:30 minutes).

The ship was sailing a 6.15 nautical mile long course and steered into a 2.35 nautical mile long 056[1] course between Grytøya and Kjøtta/Åkerøya. The 056 course was without any dangers such as underwater reefs or rocks. The course was still difficult to sail because it had few helpful contextual cues[2] to facilitate the calculation and updating of ship position. The plotted course in the chart indicated the next course as a port turn into a 336 course through Sandssundet which is a rather narrow straight between Grytøya and Sandsøya. This straight had some dangers in the form of underwater rocks. The turn in the 336 course was intended to be initiated on cue by the visual contact with a known beacon. See figure 3 for a chart excerpt of Sandssundet with the relevant plotted courses.

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The lack of contextual cues combined with darkness made the navigator aware that there was some uncertainty regarding the vessel's actual position. The fact that they were about to enter confined waters made the uncertainty of the vessel's position a possible critical threat to both safety and efficiency as they ran into the danger of grounding.

In addition to the discovery of a deviation between estimated and actual position, the navigator discovered the presence of other unidentified vessels crossing the plotted trajectory. This clearly adds to the complexity of the situation as the navigator is forced to adapt the planned course to avoid conflicting courses with the other vessels nearby. Under normal conditions (good visibility during daytime and known ship position in less confined waters) this is a routine task that navigators often solve with ease. However, under the given circumstances, this event contributed to escalation of complexity to the situation.

| Time | Agent | Statement | Action |
|------|-------|-----------|--------|
| 01:30 | Lookout | Vessel in green thirty! | |

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[1] Geographical direction of movement is denoted by a three-digit number between 000 and 359 where 000 reflects true North. The numbers increases clockwise so a straight eastward movement is a 090 course, a southbound movement is 180 and straight westward course is 270. The course 059 reflects an East – Northeast movement.

[2] Marine navigation within the archipelago depend on the use of landmarks and other navigational aids such as beacons and iron perches that are placed to mark where it is possible to sail. Since it was midnight there was only possible to navigate by the use of beacons since pillars and landmarks were not visible in the darkness.

| | Navigator | Is it the SHV[3] that lies out there | (using binoculars to visually inspect the surroundings) |
|---|---|---|---|
| | Navigator | "Ops – Bridge: Vessel in zero-five-one, below fifty meters?" | (using radio in communication with observation room below deck to request assistance to identify the observed vessel) |
| | Lookout | Incoming vessel in red five! | |

Reduced visibility due to night-time, fog and snow made the observation of beacons and posts increasingly difficult. At this point in time, the CO was not on the ship bridge, as he attended military strategic tasks in the observation room below deck, leaving the navigator without additional on-bridge support in the navigation task.

| Time | Agent | Statement | Action |
|---|---|---|---|
| 05:31 | Obs[4] | Is it a lot of fog and snow outside now? | (Communication over radio from the observation room below deck to the bridge) |
| | Navigator | Come again? | |
| | Obs | Is it a lot of fog outside now? | |
| | Navigator | Yes, there is some fog ... | |
| | Obs | Roger | |

Recurring intermittent alarms in the control panels of the ship controls informing of a malfunctioning port engine further complicated the situation. Procedure calls for establishing the criticality of the alarm by communication with engine room personnel, which in this case failed to respond to intercom calls from the navigator.

| Time | Agent | Statement | Action |
|---|---|---|---|
| 06:59 | Panel | | (An alarm goes off, indicating, indicating critical malfunction in the port engine) |
| | Navigator | | (checks the alarm and the sound and stops) |
| | Navigator | Engine room – Bridge! | (using radio and calling to the engine room from the bridge) |
| | Navigator | Engine room – Bridge! | (calls the engine room again) |

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[3] SHV = The Norwegian Maritime Civil Guard
[4] Obs = Observation room, a room below deck that among others contains advanced surveillance equipment.

The crew became increasingly occupied with the fact that they do not have the exact position of their vessel and the additional stress factors. The CO, currently situated in the observation room below deck, now ordered a reduction of speed as a remedy to the situation unfolding.

| Time | Agent | Statement | Action |
|---|---|---|---|
| 08:00 | CO | Ops – Bridge | The CO calls over the radio from the observation room below deck to the bridge |
| | Navigator | Bridge | (Holding the radio and answering the call) |
| | CO | Now its time to reduce the speed | |
| | Navigator | Yes, of course | Navigator reduces speed by using the engine throttle |

The navigator was expecting to get visual contact with a navigational cue in the form a beacon at a particular point in time as predicted by the formal navigation plan. Visual contact with the beacon were planned to indicate a timely initiation of the turn to the 336 course. The visual contact was not made, and the navigator continued to visually inspect the environment with both binoculars and radar. The crew on the ship bridge engaged in visual search of the missing beacon.

| Time | Agent | Statement | Action |
|---|---|---|---|
| 08:24 | Navigator | The beacon is not seen ... | Using binoculars while talking out loud) |
| | Navigator | Repeat course | (speaking to the plotter) |
| | Plotter | Next course: three-three-six | |
| | Navigator | Roger | |

The situation was even more complicated due to a critical alarm on port side engine sounded for the second time, and the crew was still without visual contact with the beacon. In between handling alarms and trying to establish communication with the engine room, the beacon was spotted by the plotter approximately 30 seconds after they expected the beacon to appear. The navigator immediately initiated the turn into the 336 course.

| Time | Agent | Statement | Action |
|---|---|---|---|

| Time | Agent | Statement | Action |
|------|-------|-----------|--------|
| 08:46 | Navigator | | (uses the radar) |
| | Panel | | (The alarm indicating critical engine malfunction is sounded for the second time) |
| | Navigator | | (leaves the radar and checks the alarm. The sound stops) |
| | Navigator | Call the engine room! | (speaking to the plotter) |
| | Plotter | Roger | |
| | Navigator | Port, three degrees | (speaking to the helmsman) |
| | Helmsman | Port, three – Port three on! | (confirming the order) |
| | Plotter | The beacon is seen! | |
| | Navigator | Roger! Rudder amidships! | (first speaking to the plotter, then giving rudder orders to the helmsman) |
| | Helmsman | Amidships – rudder amidships! | (confirming the rudder order) |
| | Navigator | Roger, steady as she goes! | (to the helmsman) |
| | Helmsman | One-five-zero, no, zero ... zero-five-zero degrees! | (first makes a reports a wrong course and then corrects himself and confirms the present course) |
| | Navigator | All good, helmsman | |

Then several events occur at once. Right before the turn, and at the same time as the plotter starts to call the machine room, the navigator orders the plotter to update their position. The plotter quickly updates the log and then calls the machine room, and gives the phone to the navigator. However, they fail to get the exact position of the vessel. During the conversation the alarm sounds for the third time in less than three minutes. The alarm occurs only few seconds before the planned turning point for the next 336 course. At the same time the lookout spots a danger straight ahead.

| Time | Agent | Statement | Action |
|------|-------|-----------|--------|
| 09:30 | Plotter | Hello ... the navigator wanted to talk to you | (in communication with the machinist, then hands the phone to the navigator) |
| | Navigator | Yes, there's a critical alarm on port engine going off all the time | (in communication with the machinist while at the same time using binoculars to visually inspect the environment) |
| | Panel | | (The alarm indicating critical engine malfunction is sounded for the third |

time)

| | | | |
|---|---|---|---|
| Navigator | Yes, come to three-three-six degrees | (speaking on the phone while giving orders to the helmsman and handling the alarm) |
| Helmsman | Coming to three-three-six degrees | |
| Lookout | (unclear)... vessel ahead | |

The turn to the 336 course was eventually made while avoiding the other vessels in the proximity of the ship. The plotter and navigator entered a dialogue concerning the status of the 336 course by stating details on contextual dangers to be aware of, the length of the course, and the next course to steer.

| Time | Agent | Statement | Action |
|---|---|---|---|
| 10:08 | Helmsman | Three-three-six on | (confirming that the order is executed) |
| | Navigator | Roger. | |
| | Plotter | There are no dangers in this course ... some shallow waters on port side | |
| | Navigator | Port side, right? | |
| | Plotter | Zero-point-zero-five | |
| | Navigator | What is the distance on this course? | |
| | Plotter | One-point-eight | |
| | Navigator | One-point-eight ... we must then turn forty-five by the islet on port side | |
| | Navigator | | (turns over to the chart table and discusses the chart with the plotter) |

The CO later enters the bridge and the navigator informs about the incident that occurred and that the last update exact ship position was somewhat uncertain. The navigator then orders the helmsman to change rudder control from hydraulic to electric, thus greatly increasing rudder gain.

The uncertainty of the craft's position endures and the navigator further reduces the speed. A little while later the craft's engines are running idle and the craft moves at the slowest

possible speed up the straight between Grytøya and Sandsøya (approximately 5-8 knots). The navigator attempts to locate objects that can help update their current position and inform of the next turn point. This situation lasts for approximately one and a half minute. After a couple of minutes the next beacon is spotted and the navigator and the plotter can update the position with satisfactory accuracy.

### 3.1.1. Aftermath

We performed an unstructured interview with the navigator as soon as the ship entered port. The interview took place about three hours after the incident. The navigator stated that the ship had been off its plotted course by 2-3 cables on the 056 course (360-540 metres), and after the turn into the 336 course they started the work to update ship position with sufficient accuracy. Time pressure was considerably levered due to the speed reduction, which gave time to re-establish ship position.

### 3.2. Discussion of the Kjøtta Incident: Critical Factors

A key feature of the Kjøtta incident is the uncertainty concerning ship position that is expressed through the 'non-appearing' beacon. How did the uncertainty build up during the navigation? The ship had just before the described incident followed on the planned course and in accordance to navigation expectations. How did they loose their position? The 6.5 nautical mile long course prior to the 056 course gives a clue. This course had few navigational objects that could assist in updating the position. The particularly long segment led to an accumulation of small errors in the vessel's estimated position. Vessels always drift out of course due to currents and wind, and these disturbances accumulate if not corrected. Further, moderate inaccuracies in position determination are somewhat irrelevant in open water, but become critical when entering confined waters. In this case, the movement along the 056 course and the prior course had accumulated uncertainty, and this became explicit as the visual contact with the beacon cuing the turn to the next course was not made as planned. In addition to the omitted cue, the uncertain position becomes a direct threat to safety as contextual dangers approaches.

The Kjøtta incident show how the navigator and plotter work to establish the formal demands to navigation, that is, to establish actual position. Not to know the craft's position when navigating within the Norwegian archipelago implies that the control requirements are unknown, or at best highly uncertain. The crew is aware of their approximate position (give or

take a couple of hundred meters), but the upcoming confined waters accentuate the need to establish their exact position. If the situation had escalated further and they completely lost their position the next control action would be to stop the craft completely. They would then establish their actual position by use of other means. This would be a response to the control requirements changing status from *uncertain* to *unknown*. Continuing to sail when the control requirements are unknown would be in direct conflict with their formal instructions of sailing in a safe manner.

### 3.2.1. Uncertain demands and the ability to produce variance

The crew handles the uncertainty of control requirements by increasing their ability to control the craft's movements. The primary strategy in order to increase control is to reduce speed, which entails an increase in both the craft's turn rate and the maximal functional rudder angle[5]. Maximal rudder angle is in an inverse relationship to the craft's speed; hence maximal rudder angle (and then turn rate) will increase as speed decreases (Bjørkli et al., 2007). Reducing speed also means that the crew gains more time to establish ship position. Reducing speed thus also leads to reduction of the temporal demands on the work task (Hollnagel, 2002).

A second adaptation to the uncertainty of the situation is the shift from hydraulic to electric rudder control which leads to a large increase in the gain of the rudder control. This has several effects on the ability to bring about system state changes. Lowering the speed means that the craft reacts less to low rudder angles than at higher speeds. This problem can be counteracted by ensuring that the helmsman can activate a larger rudder angle in less time. Electric rudder control and lower speeds also allow for a larger turn rate which may come in handy if they need to quickly perform evasive manoeuvres to avoid grounding.

Unpredictable variance in the environment is met by increasing the joint systems ability to bring about system state change and leveraging time. When the variance that must be met is uncertain or not known the crew maximizes the ability to bring about changes in system states. The adaptations allow for a more efficient handling of the possible dangers that may

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[5] Maximal rudder angle means that there is an upper limit to the amount of rudder angle that will lead to an increase in turn rate. If one increases turn rate beyond the maximum the vessel's turn rate will not increase. Instead the vessel will begin to shake violently as the increased energy output from the rudder's deflection of water is transformed. The navigators try not to exceed the maximal turn rate as this can damage the ship.

appear due to the uncertainty of their position. Stated in the terms of the law of requisite variety (Hollnagel & Woods, 2005, Conant, 1969), the navigator and CO reduces speed and increases rudder gain in order to be able to produce system variance that are *functionally adequate* with respect to the unexpected or unknown variance in water depth. The Kjøtta incident is in this sense a real-life example of how human operators adapt to satisfy the law of requisite variety by anticipating future control requirements and altering the control possibilities.

### 3.3. The Indre Folda reflections

The reflections reported here occurred during a navigation exercise at Indre Folda region south of Rørvik in Norway. The observations were carried out during low tide at daytime in good visibility and weather conditions. The Indre Folda is a particularly demanding stretch with underwater reefs, shallow water, small islands and narrow passages. The low tide made the manoeuvring even more challenging by lowering the sea level and thus reducing the areas where the ship can travel without grounding. The demands on crew and vessel are even further enhanced by the fact that the ship manoeuvres the Indre Folda passage at top speed (approx. 32 knots). The navigation exercise that took place was a part of the Royal Norwegian Navy's navigator training programme. The observed reflections are similar normal non-training circumstances. This type of communication between navigator and CO is common during regular military exercises and operations and is considered part of normal operation.

The chief acts both as a tutor for the navigator and as a conversational partner who gives advice and educated opinions on the navigator's actions and choice of trajectories. The conversations of navigator and CO are constrained by continuously changing task demands. Often several formal and informal conversations are intertwined and concurrent (Andersen, 2000). The dialogue between the CO and the navigator was also observed to occur simultaneously with other navigation and manoeuvring tasks. The navigator talked and listened to the chief while at the same time issuing rudder orders to the helmsman and asked the plotter for the next courses.

The following sections present four verbal reflections where the navigator and the CO reflects upon the operation of the ship as they are faced with specific challenges during their journey through Indre Folda region.

### 3.3.1. First reflection: Prospective adaptation to future challenges

The first reflection between CO and navigator took place in a part of the Indre Folda where the ship had sailed earlier that day. The CO commented upon the positioning of the vessel and gave advice on the handling of the vessel in relation to contextual cues and future dangers. The issue at hand here was how to find a trajectory that allowed for both a good turn and that enabled the craft to pass both port and starboard dangers at a satisfactory distance.

| Time | Agent | Statement | Action |
|---|---|---|---|
| 18:10 | Navigator | I think we're in a better position now | (referring to previous journey earlier the same day) |
| | CO | Yes, now you're stemming towards the far iron perch | (pointing to a set of perches in the upcoming waters) |
| | Navigator | … far perch … | |
| | CO | Then you'll get some space port side … and you'll get an ideal trajectory | |
| | Navigator | So, then I'll get to the two-three-four when … | (making gestures indicating a starboard turn, and verbally referring to the next course which was 234) |
| | CO | Yes, then you'll have a damn fine line through, right? … without you going in there and having to pull the ship through, and you'll have a nice clearing to the dangers on starboard side, and to the dangers on the port side, when you get down there … and you have cleared the one on starboard. | (making gestures indicating directions and turning movements while explaining.) ("… having to pull the ship thorough, …", refers to a hypothetical turn in between the dangers) ("…the one on starboard." refers to the dangers on starboard side) |

This reflection pointed to a situation where the crew attempted to optimize action space by manoeuvring in a way that satisfied both safety and efficiency concerns. The main problem faced here was the adaptation to particular circumstances by the use of contextual navigation cues to enable a safe passage between starboard and port dangers (as mentioned by the CO *"and you'll have a nice clearing to the dangers on starboard side, and to the dangers on the port side"*). The navigator must furthermore take into account the sequential nature of the

phases of the turn and their respective characteristics in order to adapt to the control requirements of the region. This last aspect is formulated by the CO's comment on the need to maintain a straight course through without making a turn ("…without you going in there and having to pull the ship through…").

**3.3.2. Second and third reflections: The initiation and timing of turns**.
The second and third reflection both involved the navigator and CO retrospectively discussing the use of rudder orders and manoeuvring strategies in two particularly difficult segments defined by many underwater reefs marked by iron perches. Both segments demanded many small and rapid corrections of the course in order to traverse safely. The second reflection reported herein occurred after they had passed the narrow entrance to the Indre Folda Region. The third reflection was observed after the sharp turn out from the infamous "Trail of Perches" which is a long and narrow passage among several sunken rock marked by perches.

3.3.2.1. Second reflection – "The 'more than enough' turn"
The second reflection occurred in a short period of time where the workload was low and the CO and navigator talked about a rather narrow passage at the northern entrance of the Indre Folda region. This reflection is related to the problem of appropriate use of rudder angle to make small corrections in confined waters. The error margins in this area are small because of the closeness to sunken rocks and the momentum in the ships movement. Thus, any untimely or inappropriate rudder angle change that set the ship off the planned course are problematic since any lateral deviations from the safe course take time to correct.

| Time | Agent | Statement | Action |
|------|-------|-----------|--------|
| 32:10 | CO | Yes, the use of rudder on the entrance to Indre Folda is a bit … | (retrospectively commenting on a particularly demanding segment of the region they have just manoeuvred) |
| | Navigator | Come to port side five to two-zero-zero degrees | (to the helmsman) |
| | Helmsman | Two-zero-zero degrees | (confirming order) |
| | Navigator | Yes, its more than enough down there, yes | (to the CO, pointing to a particular turn inside entrance to The Indre Folda Region) |
| | CO | Yes, one or two degrees if you want to change the course, right, | (discussing the use of rudder angles and timing to make the vessel turn |

*rather than being too early by          appropriately in the given instance)*
*using two or three degrees, then*
*the ship turns way too much*

Correcting a given course with only a few degrees in confined passages represents is challenging due to the manoeuvring properties of the Hauk-Class (see Bjørkli et al., 2007, for a thorough description of the Hauk-Class' turning capabilities). The initiation of a turn is, as mentioned, implemented in three phases determined by interaction between hydrodynamics and the ship's hull and rudder system. The initiation of the second phase initiates a rotational momentum which takes time to correct if the turn was too sharp. This has implications for the timing of the turn. If, on one hand, the ship comes too fast (meaning that the response to the rudder angle change is too large for the situation) or is initiated too early, the rotational momentum needs to be counteracted so that the ship does not collide with dangers on the inside of the turn. If, on the other hand, the turn comes too fast or is too small, the ship will turn too slowly to make it through the turn.

3.3.2.2. Third reflection – "the six-thirteen turn".

The third reflection accentuates the observations made in the second reflection and involves the challenge of the balancing of timing and choice of rudder angle. The reflection is made retrospectively following the incident at the sharp port turn out of the "Trail of Perches" (the actual incident and the rudder orders given by the navigator is reported as "the Trail of Perches" in Bjørkli et al., 2007, p. 74 and 76). The navigator entered the turn by ordering a three degrees port rudder angle. The ship responded slowly and too little, so the navigator ordered a five degree port rudder angle. This was still not enough, so the navigator ended up increasing the rudder angle in rapid succession via seven degrees up to ten degrees as the ship entered and passed through the sharp port turn. The ship took a wide turn and got close to the sunken reefs and shallow waters. Immediately after the turn the CO responded to the late and gradual rudder orders, and pointed out ways to accommodate the craft's turn rate.

| Time | Agent | Statement | Action |
|---|---|---|---|
| *41:45* | *Navigator* | *I got to induce more turn to open it up* | *(Reflecting on the turn out from The Trail of Perches)* |
| | *CO* | *Yes, it a kind of 'six-thirteen' mentality* | *(6-13 is a label of a torpedo used in the Norwegian Royal Navy – known for its limited steering abilities* |

| | | | |
|---|---|---|---|
| | | | *resulting in wide turns when changing course)* |
| | *Navigator* | *Six-thirteen mentality?* | |
| | *CO* | *Yes, it is always turning wide, right, like you start with one degree, then two, then three, then four, then five and then all the way up to thousand.* | *(referring to the behaviour of the 6-13 torpedo in a third-person perspective- as an analogy to the turn made by the navigator).* |
| | *CO* | *Its better to get the ship start turning, then adjust it as she goes* | *(He then comments on a better strategy for handling these types of situations).* |

The second and third reflections involve the same principle of adapting the ship turning characteristics to the particular situation. The challenge of manoeuvring in narrow passages is to use a rudder angle that initiates an acceptable rotational movement at an acceptable time.

The importance of the timing and the ship's response to the rudder angle get accentuated by comparing of the two reflections. The second reflection followed a situation where the navigator ordered three degrees rudder angle in order to make small adjustments to the craft's course. This adjustment initiated a larger rotational movement than expected, and the rotational movement had to be counteracted to avoid a possible critical incident. The third reflection was related to the initiation of a small rudder angle which initiated a too small rotational movement too late. This lack of response had to be met by a continual increase of rudder angle in order to not run aground on a reef in front of the vessel.

### 3.3.3. Fourth reflection: Navigating to improve manoeuvring

The fourth reflection is a prospective planning of a situation where the craft comes from an open segment of the Indre Folda and is about to make a starboard turn into a narrow passage. The challenge in this situation is to find a good way to enter the narrow passage in a way where variability in lateral positioning in the sailable track is minimized when the ship enters the passage. The CO helps the navigator in this task by pointing out the presence of a mast that the navigator could stem towards.

| Time | Agent | Statement | Action |
|---|---|---|---|
| *37:39* | *CO* | *Do you see the mast down there?* | *(pointing to the area in front of the* |

| | | |
|---|---|---|
| | | *ship)* |
| *Navigator* | *The mast there …?* | |
| *CO* | *Stem towards that, and you'll do just fine* | |
| *Navigator* | *Come port side to two-two-zero degrees* | *(to the helmsman)* |
| *Helmsman* | *Two-two-zero degrees* | *(confirms rudder order)* |
| *CO* | *(unclear) … to have the ship lined up straight as you go in, you got a straight line through, you not in a turn, (unclear)…you can go straight and then just dive into the turn* | *(making gestures indicating directions in the waters ahead)* |
| *Navigator* | *I never though of that* | |
| *CO* | *There you got it* | *(referring to the current ship position and direction )* |
| *Navigator* | *Repeat next course* | *(to the plotter)* |
| *Plotter* | *Two-four-three* | *(repeats next course)* |
| *CO* | *You see that it eventually opens up, right? Just go head on. Set a course and go straight in.* | *(making gestures indicating directions in the waters ahead)* |

This segment before the narrow passage was deep and open enough to allow for a rather long and slow turn into the passage. The CO points out that the navigator does not have to make this long turn (which demands continuous supervision of the turn rate) and instead may stem towards a mast placed on the island. The mast was not part of the traditional navigational aids in Indre Folda. Stemming towards the mast allowed the navigator to make a fast and clean turn that gave time to align the craft into a straight course before entering the narrow passage. Figure 4 presents the possible difference between the two strategies the CO and the navigator intended to perform.

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Please insert Figure 4 about here.
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**3.4. First and fourth reflections: Optimizing control**

The first and fourth reflection involves the prospective optimization of a turn so that the course through a narrow passage occurs in an acceptable manner. The optimizing of movement trajectory through the region demands that the crew takes into account the craft's current position and movement dynamics and evaluate these factors up against future dangers and demands. This evaluation must also be made in accordance with the formal instructions of navigating safely and efficiently.

The ability to optimize the situation show that the CO and the navigator have an explicit understanding of the craft's movement dynamics in that they can prospectively evaluate the craft's placement and movement some time into the future. The important finding here is not only that there is some type of optimalization going on, but rather that the navigator and CO seems to prospectively evaluate the pros and cons of the situation. They seem to adapt to the combination of control requirements and control possibilities as they choose the specific trajectories. It thus seems that the navigator and CO adapt their understanding of the current control situation as it unfolds (See also Bjørkli et al., 2007 for further examples).

The fourth reflection from Indre Folda show how the CO combines local geographical knowledge with navigational expertise by using external aids to improve the craft's trajectory into a narrow passage. The choice is between following a straight course and then to turn sharply into another straight course (the CO's suggestion) through a narrow passage or to make a long gentle turn into the passage (the Navigator's intention). The navigator's choice of using a single long turn that is modulated as they approach the narrow passage leaves less time to straighten the craft's course before they enter the narrow passage. The CO's strategy, on the other hand, allow for more time to ensure a straight course through the passage since the turn is finished well before they enter the passage. The narrow passage does not allow for much deviation sideways positioning. Hence, it is better to complete the turn and adjust the craft's position and heading *well before* they enter the narrow passage. Making a sharp turn which are cancelled out before they entered the passage is thus much less labour-intensive than entering the passage while still in a turn. Choosing to make many small corrections while entering the narrow passage (as the navigator intended) will increase the possible variance that must be handled.

The issue at hand here is that one should make the adjustments to the ship's course when one have the time and space for it. The navigator's main challenge in such a situation is to find a good balance between the minimal numbers of corrections necessary to meet the control requirements that are present. The difference between the CO's and Navigator's control strategies is directly related to the reduction of lateral variance and handling of residual rotational momentum when entering the narrow passage.

## 3.5. Second and third reflections: The timing of turns

The second and third reflections are retrospective reflections involving the same underlying manoeuvring problem. It reflects the problem of setting the system up for action, rather than acting directly. This is done by the use of the turning strategy called "heating the turn[6]" in which the navigator initiates the rotational movement prior to making the actual turn. This is done by activating small rudder angles which starts first phase of the turn without initiating the second phase consisting of the rotational movement. This is a form of preparation of the system for upcoming course changes. The basis for this is the phased initiation of rotation that is due to the non-symmetric hydrodynamic forces acting on the hull and rudder.

The advantage of this strategy is that rudder angle increments in the same direction have a faster effect on the craft's turn rate after the vessel has started the rotational initiation. This improves the predictability of the vessel's movement and turn rate since it reduces the temporal lag between initiation of rudder angles and the actualization of the rotational movement.

The problem in the second reflection was the over-initiation of the turn rate using three degrees, rather than one or two. This led to quick and sharp turn which had to be corrected to keep the vessel on the safe path between the shallow rocks. It is this effect the CO refers to when he states "… *rather that than being too early by using two or three degrees, then the ship turns way too much*". The problem in the third reflection is ordering too little rudder angle in the beginning of the turn, which means that the boat takes more time to initiate the rotational movement. When this rotational movement comes it was too small, thus increasing the demand for further rudder angle in order to not ground on dangers ahead. The challenge in

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[6] The Norwegian term is "varme tørnet" which is directly translated to "heating the turn", indicating that one prepares the system to act in given manner which will not require any additional time lag or additional actions on the side of the navigator.

both these reflections is to find the shifting point between turning and non-turning, between the initiation of the first and the second phase.

The relationship between first and fourth reflections versus second and third reflections is that the use of external contextual aids and local knowledge in order to optimize the movement through the area depend on explicit knowledge of the vessels steering capabilities and turning dynamics. The second and third reflections give us an insight into how the navigator and chief judges the situations they encounter in terms of the steering capabilities of the joint system.

## 4. General Discussion

What do the present observations tell us about the operator's strategies and their models or understanding of the situation? The aim of this article is to find whether the control situation framework (Petersen, 2004; Bjørkli et al., 2007) contains a description of the models the users have of themselves and the technical system, thus fulfilling Hollnagel's second requirement to dynamic models of human-technology systems (Hollnagel, 1993).

### 4.1. The navigator's control strategy: Reduce control demands on short time-scales.

The comparison between the Kjøtta incident and the two sets of reflections in Indre Folda show that the relative importance of navigation (e.g. knowing the ship's position, knowing next course, keeping to planned route) and manoeuvring (e.g. steering the ship according to next courses, maintain satisfactory distance to dangers, adapting current course and position to improve future manoeuvring).

In the Kjøtta incident the navigators are met by a complex navigational task where the demands for manoeuvring are low (straight long courses few immediate dangers). The uncertainty of the ship's position makes the crew adapt to the situation by maximizing their control possibilities and, at the same time, reducing the control demands. These adaptations could be described as preparing for efficient control actions on shorter time-scales without needing to alter system parameters (e.g. reducing speed or altering rudder gain) before they initiate evasive manoeuvres. When control demands are highly uncertain, the crew prepares the ship for maximum state change. Thus, the crew adapts by prospectively altering the control possibilities over the craft's movement (lower speed, increasing gain of rudder controller) that ensures a functional adequacy related to a set of possible but uncertain control

requirements. By reducing speed, they also lower the prospective control requirements, by getting more time to perform control actions.

The passage through Indre Folda, on the other hand, involves a larger focus on manoeuvring and less on navigation as such. Control requirements are more related to manoeuvring to avoid sunken rocks and to maintain a good position for future manoeuvring. Hence, control actions in the Indre Folda reflections are more subject to time pressure (i.e. must occur on shorter time-scales), but the control requirements are quite clear and explicit.

In the first and fourth reflection the crew is faced with a task that involves both navigation and manoeuvring. The crew must use contextual cues to navigate in order to optimize the possibility for manoeuvring through narrow passages. The movement from rather open waters to confined waters is a challenge that relates not only to navigation, but also to the manoeuvring and reduction of lateral trajectory variance through the region. The first and fourth reflection gives us an insight in the on-line planning that the crew performs before entering confined areas where manoeuvring is a primary task. By using both local geographical knowledge and knowledge of the vessel's movement capabilities the crew adapts to particular demands by reducing variance on short time-scales. The reduction of variance and uncertainty on shorter time-scales also increases predictability of the ship's trajectory, and henceforth reduces the need for feedback-controlled adaptations that must be initiated quickly.

In the second and third reflections the crew is faced with difficult manoeuvring where the time-frame for performing the next control action is in the time-range of split-seconds to seconds. In order to be better able to adapt to the situation the navigators uses a strategy called "heating the turn" by initiating a small rotational movement in the vessel before the actual turn is supposed to be performed. This increases the ship's responsiveness to further rudder angels *in the same direction* as the initiated turn. The strategy has adaptive interest as the increased responsiveness and reduced time lag between rudder angle changes and initiation of turn increases the predictability of the turn. The strategy also allows for faster feedback on modulations so that further changes can be made.

The layout of the environment in combination with the task requirements involves different time-frames for adaptation (Hollnagel, 2002) and affects which control task (navigation

versus manoeuvring) are the most pressing (Hollnagel, 1993; Hollnagel & Woods, 2005). The difference in control tasks and time-scales for control actions are, despite the difference in time-frames and context for operation, similar in structure. The three observations all show how operators control the system in ways that eases the maintenance of control on shorter time-scales. They do this by either maximizing the ability to react to uncertain and possible imminent critical situation (the Kjøtta incident), by reducing the environmental variance related to their manoeuvring (the first and fourth reflection in Indre Folda), or by preparing the system for upcoming turns (by 'heating the turn' in the second and third reflections in Indre Folda). These observations can be described at a general level as *the reduction of unintended variance on short time-scales*. This argument may be seen to reverberate Bernstein's (1967) understanding of how coordination is achieved – by reducing the number of independent variables that need to be controlled. Rasmussen (1990) points out a similar view on coordination in complex sociotechnical systems. He argues that workers often spend as much time to assess the number of degrees of freedom and the significance of them as actually responding the system performance. In this sense, modern complex systems represent the challenge of problem formulation and diagnostics as well as problem solving and operator intervention, and the integration of those two are at the heart of skilled work practice.

The control strategies observed in the Indre Folda reflections and the Kjøtta incident are tied up to the physical and temporal constraints for the ship's steering capabilities. All control actions that have to be performed on short time-scales *must* be based upon the nature of the ship's turning characteristics. Effective control demands that the crew take into account the specific sequential unfolding of the ship's turning characteristics and the uncertainties that are related to this dynamic process. The navigators must adhere to the physical constraints of their work domain (see e.g. Vicente, 1999, for a discussion).

## 4.2. What models do experienced navigators use?

The knowledge of the control strategies used by experienced navigators give insights into the models or understanding the navigator have of the situation. Adaptations made to maintain control in a navigational task is exemplified by the Kjøtta Incident which shows that experienced navigators are sensitive to any significant changes in the contextual variance. They furthermore adapt to the increased uncertainty of future contextual variance by increasing their ability to control the craft's movement. This joint adaptation to altered control requirements (uncertainty of position of underwater reefs and rocks) through the increase of

control possibilities (turn rate, time constraints) is an example of adaptations to possible future control situations. The navigator does not reduce speed due to dangers that are present "here-and-now" but rather because the uncertainty of the situation demands that he must maximize the ability to meet future dangers. The observations of the Kjøtta incident indicate that the navigator adapts prospectively to the joint set of control requirements and control possibilities, thus indicating that the navigator's model of the system is tied to the system's particularized control situation as it is expressed in the contextual requirements for control and the specific control possibilities.

The strategies of preparing the joint system for control actions made on short time scales can be understood as a function of the navigators' model of the situation and the situation in itself: Firstly, high speed craft manoeuvring is first and foremost guided by the constraints set by the immediate environment. The environmental constraints also directly affect the time constraints that navigators have to perform control actions. Secondly, the capability of the craft's effector systems to bring about system state changes is conditional upon other contextual factors such as wind, currents and waves (Petersen & Nielsen, 2001; see also von Wright, 1971, p. 66ff). These contextual factors are not readily perceived by the human operator and thus create uncertainty of the actual capability of the craft's effector systems. By reducing the need to make quick adaptations on shorter time scales the operators give themselves more time to deal with unanticipated changes in the craft's movement dynamics. The short available time to perform corrective actions is not only a problem for the navigator, but it may also lead the joint system too close to its operative boundaries, thus creating a possible critical incident. Thirdly, by adapting to particular circumstances by reducing the workload on shorter time scales the navigators can effectively reduce the need to make many small adjustments to the craft's movement trajectory, thereby also reducing the degrees of freedom that need to be controlled.

Both in the prospective and retrospective reflections made in Indre Folda the navigator and CO discusses actively how to manoeuvre in difficult confined waters. The results indicate that experienced navigators perceive the situation *in terms of* the possibilities and constraints for action. In other words; experienced operators perceive the affordances and constraints for not only their own actions, but also for the joint human-technology system. This possibility is supported by experimental evidence that indicate that experienced drivers of a wide range of vehicles in some way extends the perception of passable apertures to also cover the vehicle

that they control (see Shaw, Flascher & Kadar, 1995, for a theoretical and empirical review). This close connection between experienced operator's and their work domains has been empirically noted before, particularly in supervisory process control (metal manufacturing industry; Norros, 2004) where the physical separation of operator's and technology are more clear-cut than in the case of marine high-speed craft manoeuvring.

Operators can in this sense be understood not only as initiators of effector systems, but also as *extended operators* that include system dynamics in the perception of action possibilities and constraints (Øvergård et al., 2008; Øvergård & Hoff, 2005). In this situation, the operator must have an understanding of the *expected variability* of the craft's movement capabilities as it is actualized in particular settings (see Bjørkli et al., 2007). The uncertain nature of high-speed craft manoeuvring capabilities indicate that the operator does not use a model of the turning capabilities of the vessel as a formalized description of the ship's effector systems, but rather as *a set of possible realizations* of the initiation of a given et of rudder angles.

## 5. Conclusion

The observations and the navigating crew's reflections indicated that the control situation may be a possible way of modelling the operators understanding of the controlled system.

The concepts of control possibilities and control requirements reflect basic parts of the navigators' control strategies and models of the work domain. The navigating crew's strategies and verbalizations indicated that they explicitly balanced control possibilities up against control requirements. The reflections at Indre Folda also indicated that these strategies were guided by an explicit knowledge of the how the physical and temporal dynamics were *actualized in manoeuvring*. This element was particularly expressed in the observation of the strategy called "heating the turn". This does not mean that the navigators used a formalized specification of the characteristics of the effector systems as such (which would be useless due to unpredictable contextual variance). The navigators' model is rather based on the *functional expression* of the interaction between hydrodynamics and effector systems. The nature of the physically constrained (but unpredictable) functional expression was taken into account by the navigators by the observation that they acted as to reduce unpredictable variance on short time-scales.

The observations and reflections of actual work performance indicate that the main concepts in the control situation framework can be used to reflect the operator's models as used in authentic work situations, thus fulfilling Hollnagel's (1993) second requirement to dynamic models of human-technology systems.

# 6. References

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Figures

Figure 1: The Hauk-Class vessel



Figure 2: The navigation team's workplaces at the ship's bridge.
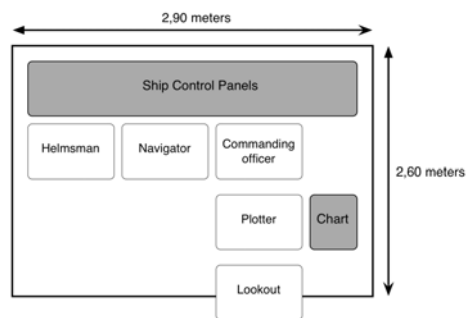
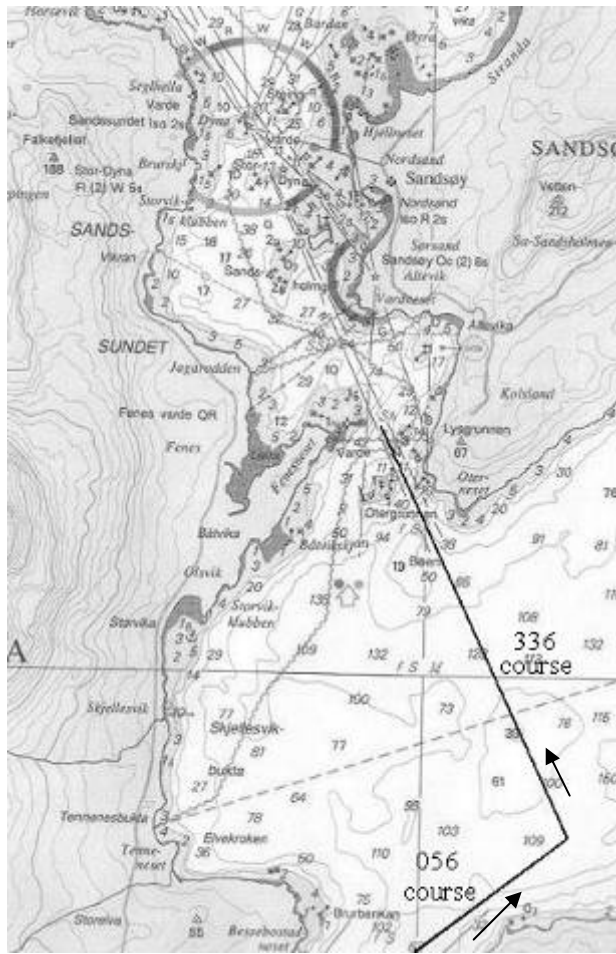Figure 3: Map over Sandssundet



Figure 4: Control strategies in the fourth reflection
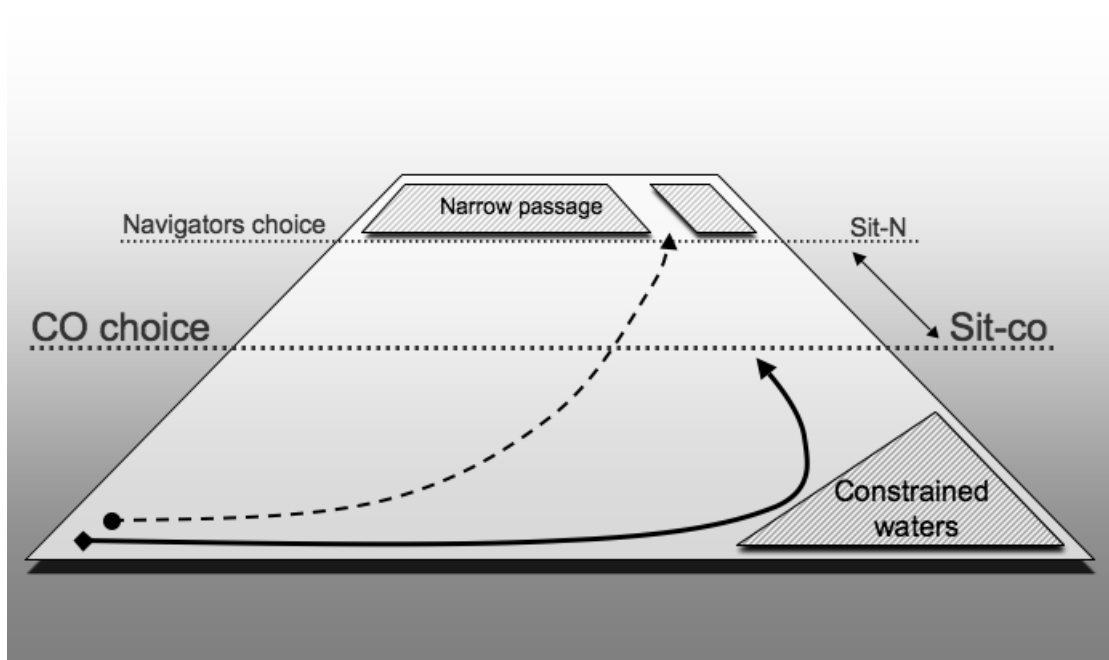
Figure captions


Figure 1: Fast patrol boat of Hauk-class during exercises in November 2004. Photo by C. A. Bjørkli.


Figure 2: Left: Overview of the bridge. The ship's bow is up. The figure indicates the positioning of the five crew members involved in navigation and manoeuvring.


Figure 3: Map overview over Sandssundet. The black lines show the approximate planned courses. The ship came into the map on a 056 course heading N-NW. The crew had planned to make the turn into the 336 course heading N-NE when the beacon shifted from green to white. Map excerpt fra sea map no. 80 reproduced with permission no. 591/08 from Statens Kartverk Sjø.

Figure 4: Presentation of the hypothetical trajectories following the strategies used by the CO and the Navigator. The dotted line represents the Navigator's strategy, while the whole line representing the sharp turn represents the CO's strategy. The difference between these strategies can be seen as the difference between the lines named Sit-N and Sit-co which show the space available for modulations of the craft's trajectory into the narrow passage. The CO's strategy allow for more time to adjust the craft's course, and hence is more robust when it comes to adapting lateral variance before and during the trajectory through the narrow passage.