Is it a bug, or is it a feature?
Taking the social organization of work into account in human-machine systems design*

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ABSTRACT

In analyzing work with a view to introducing new technologies, a systematic source of inappropriate or inadequate design decisions, which eventually may cause breakdowns and accidents, is posed by the social organization of work if it is not taken into account. This paper argues that analysts engaged in making decisions about the allocation of functionality between human actor and technology should carefully and systematically investigate the social organization of work. The existing environment may for instance have hidden or invisible affordances which, when removed as part of a technological change, may be sorely missed. To illustrate this we report from a field study of ship navigation. Complex time-critical cooperative work like navigation requires much effort on coordinating the distributed activities. Due to the nature of the work, decision making and coordination must be handled 'on the fly' while the work is ongoing. Hence, mutual awareness and interaction among the actors become essential. It is concluded that for analyzing this type of work the social organization of the work, the complexity aspects of the field of work, the hidden functions of the existing work arrangement, and the facilities provided by the applied communication means must be systematically addressed.

1. Introduction

Firmly rooted in control theory and thus offering a rigorous approach to the analysis and modelling of human work, the 'man-machine systems' approach has been quite influential in the design of control facilities for work in complex technical settings (Edwards and Lees, 1973; Edwards and Lees, 1974; Sheridan and Ferrell, 1974; Singleton, 1974; Sheridan and Johannsen, 1976; Rijnsdorp and Rouse, 1977; Rouse, 1980; Hollnagel and Woods, 1982; Johannsen and Rijnsdorp, 1983; Rasmussen, 1986; Hollnagel et al., 1989). During the last decade or so, however, some inherent limitations have become evident:

The human-machine systems approach is based on the presumption that there is only one operator or, in the case of multiple operators, that the cooperative effort is so easily and so well coordinated that one can safely disregard the cooperative aspects and proceed as if the human component of the human-machine system behaves as a singularity with the biological and cognitive characteristics of human actors, that is, as if there is only one operator. However, when the human component cannot be treated as a singularity, and that is the case in most complex domains (civil avionics, maritime navigation, process industries, etc.), a quite different set of issues emerges and must be addressed systematically: How are tasks and responsibilities

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allocated and reallocated among actors in the course of the activity? How do actors determine who is responsible to take certain actions in the face of a new situation? How do actors manage to act in a sufficiently concerted way, in the face of partial knowledge? How do actors know what colleagues have done or are doing? What do actors know of the circumstances facing their colleagues and how do they get to know that? How do actors make their own actions, their circumstances, and their intentions known to their colleagues? Is it at all possible to determine which actors should be considered part of the particular human-machine system? Does the composition of the ensemble change dynamically, according to the conditions at any point in time? And so forth.

On the other hand, the human-machine systems approach is based on the presumption that the technical component of the human-machine system is well defined in terms of boundary and behavior. However, in most complex technical settings, this presumption is also problematic: The technical system may be open in the sense that it may be difficult or even impossible to delimit it; it may interact with other systems and hence other man-machine systems in the environment in different, varying, or even unpredictable ways and degrees. Even if the boundary of the system can be defined accurately, the ‘system’ may be so complex and dynamic or so poorly understood (cf. Perrow, 1984) that the system eludes sufficiently accurate and detailed modelling for the human-machine systems approach to be anything but an inspired metaphor to systems design.

In all this, the human-machine systems approach subscribes conceptually to control theory. The approach accordingly conceives of its domain as a closed system, consisting of two component systems: human actor and technical system, which has a well defined goal, i.e., a system state to be reached or preserved (cf. Ashby, 1956, pp. 4, 219 et passim). It is extremely useful to conceive of, say, a vehicle and its human operator as a system in this sense, and the approach has thus been quite successful in modelling manual control, i.e., cases where the human operator is in the first-order control loop. However, control theory starts faltering as a frame of reference for analyzing human work the further the activity to be understood and modelled is removed from the first-order control loop (e.g., supervisory control, problem solving) and in many, if not most, work settings this conception can be quite misleading when applied rigorously; think of design work, for instance.

The purpose of this paper is not to discuss the human-machine systems approach in general but merely to address some of the issues that emerge as soon as we face the fact that a particular domain of work involves multiple actors and that the cooperating ensemble cannot be treated as a singularity, that is, when we face the fact that the work is socially organized: how do we do that? There may not be a straightforward answer to that because the coordinative activities of a cooperating ensemble are seamlessly and inexorably integrated in the ‘primary’ activities. Actors exploit the features of existing technologies to do the job more efficiently, more safely, more timely, etc., and the existing environment may thus have hidden or invisible affordances, which, when removed in the course of technological change, may be sorely missed.

A striking illustration of this problem has been provided by a study by Kasbi and Montmollin (1991) which explores the impact on cooperative work practice of the planned radical computerization of control room design for the French 1500 MW power plants of the N4 PWR series. In order to study the impact of this putative ‘technological leap’, it was decided to connect a prototype of the advanced computer-based control room to a 1300 MW PWR process simulator called S3C. Operators running the S3C were observed and their performance was compared with field study findings from conventional control rooms.

In the power plants in question, two operators manage the control function. In some control situations (start-up or shut-down of plant units, incidents, etc.), there are prescribed, detailed procedures which govern the allocation of tasks between the two operators. The procedures are based on a subdivision of the process into a Primary side (nuclear reactor) and a Secondary side (water and steam). However, in most control situations, the operators are left free to decide how to allocate tasks between themselves. The organization of work — in particular, the allocation of the Primary and Secondary systems between the operators — is far more flexible.

Since the plant is a highly integrated technical complex, the activities of the two operators are complementary and interdependent. In fact, 'two operators are really needed to control the process' (Ibid., p. 281). Therefore, in order to carry out their work, they must act in a highly coordinated fashion, and to do so each them needs access to reliable information on the state of the plant as a whole.

In traditional control rooms in nuclear power plants, information on the state of the plant is displayed on a panel that is several meters long; it is located in a room in which the two operators both work. By contrast, in the S3C control room design each operator has a computer workstation. While these workstations provide access to all relevant control data, S3C have some disruptive effects on work coordination. At the beginning of a session, the operators normally agree on the allocation of the Primary and Secondary systems. However, during their work, they often have to handle tasks concerning the side of the system initially assigned to the other operator. In a conventional control room this poses no problem. Each operator is continuously informed of the part of the process monitored by the other operator from the position of the other in relation to the instrument panel. From the changing positions of his colleague in the room, each of them can effortlessly infer what the other is up to. Furthermore, he only has to take a few steps to get a clearer idea of what is happening and so in doing he does not need to disturb the activities being carried out. Awareness is essential: 'Interactions between operators (oral exchanges, glances, movements to and fro), on the one hand, and the information sources available in the control room (alarms, pictures, mimic panel) are the means the operators working in pairs use to monitor the overall process and/or the other's activity' (ibid., p. 282). That is, the specific characteristics of the conventional interface to the control system of the plant provide cues for operators to develop and maintain the required reciprocal awareness without forcing them to resort to verbal communication. The formation of this reciprocal awareness is not supported by the design of the control room.

The importance of mutual awareness has been demonstrated compellingly by a number of studies of the social organization of work. For example, a study by Heath and Luff (1992) of a control room in the London Underground system, uncovered some of the simple and yet powerful techniques by means of which operators fluently and seamlessly coordinate and integrate their individual activities through monitoring of what others are doing, making one's own activities publicly visible, directing the attention of others to certain problems in delicate and unobtrusive ways, etc. Similar studies of work in a dealing room in the City of London (Heath et al., 1993) revealed similar ways of engendering mutual awareness among the actors as well as other means (e.g.., 'open cries').

Another often cited set of studies are those of control work at the air traffic control center outside London (cf. e.g., Harper et al., 1989; Hughes et al., 1993). These studies investigated, inter alia, how careful manipulation of artifacts (e.g., flight strips) supported mutual awareness among the air traffic controllers and provided a medium for coordinative actions.

Hutchins (1995) reports on a field study of navigation by the crews aboard large navy vessels. He argues that different personnel have distinct responsibilities and specialized tasks, but since the actors are extremely interdependent in their work the activities are handled in close coordination with the tasks and activities performed by others. Ensuring mutual awareness and distributing information concerning the state of affairs and actions taken thus become the most essential coordinative activities. Hutchins concludes that rather than following a master procedure the actors on the bridge of a large ship coordinate their activities through their interactions.

The studies and the approaches for providing collaboration support mentioned have contributed considerably to providing a conceptual foundation for the design of cooperation technologies. Rather than adding to or discussing this body of work on how an orderly accomplishment of complex cooperative time-critical work is achieved, our aim is to reflect on some methodological problems in addressing these types of work settings.

To illustrate our point and provide a basis for the methodological discussion we will describe an everyday situation of a crew navigating a container carrier inbound for Southampton harbor. The case is based on a series of field studies of bridge crews navigating large container carriers. Firstly, navigators working on the bridge were observed during seven full days (8-9 hours each) over a period of one month. Some of the sessions were part of courses in ship handling and casualty prevention for experienced navigators. These navigators were 'sailing' in a high-fidelity full-mission simulator. All actors commented on the use of the simulator that it was very close to real-life navigation. We also attended the debriefing sessions where experienced navigators analyzed and evaluated the performance of the crews. Other observations were made on the bridge of a ferry-boat. Approximately half of the observed missions and all the debriefing sessions were video-taped. In addition we have had a number of informal interviews and talks with experienced captains and pilots which can be characterized as open-ended qualitative interviews (Patton, 1980). Finally, but not least, one of the authors has recently concluded ethnographic studies aboard two of the worlds largest container carriers on two tours which together included more than 30 harbor approaches on three continents over altogether three months. These ethnographic studies have resulted in more than 120 hours of video recordings of time-critical crew performance, large amounts of annotated replay data, and numerous discussions and interviews. Due to limited time these studies have not yet been systematically analyzed and in this paper they mainly serve as 'deep background'.

2. Ship navigation

While drawing on material from the whole series of field studies of both container carriers and ferries, we focus in particular on the navigation performed aboard a 300 meter long container carrier inbound for Southampton harbor.

2.1 Navigation in general

Basically the movements of a sea-going ship are determined by the interactions of controllable and uncontrollable physical forces. From this perspective safe navigation is concerned with applying the controllable forces on the uncontrollable forces in ways that result in the desired movement of the ship; the objective being to transport the ship and its cargo between ports in quick and safe ways.

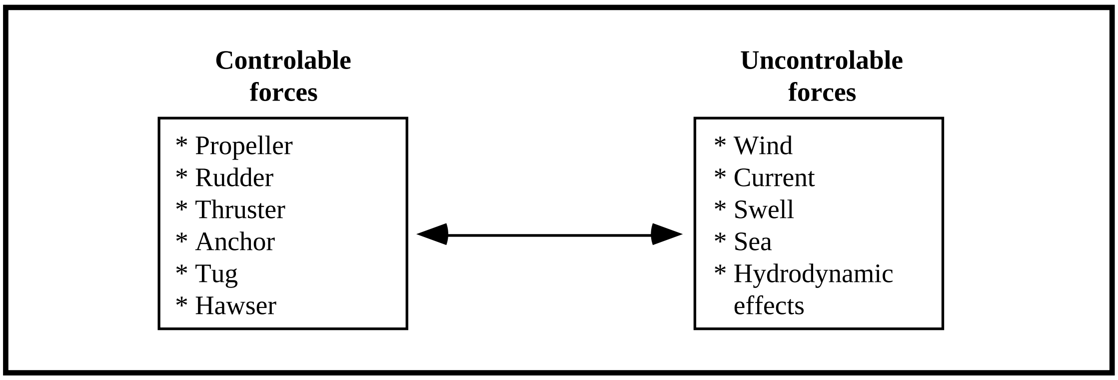

Figure 1: Controllable and uncontrollable forces.

Ships of the size of the one considered in this study have quite limited maneuverability. During the voyage it will often be the case that the uncontrollable forces work strongly against the desired navigation and at times they might even be the most powerful. Therefore, the course segments and in particular the course changes are planned and plotted on sea charts prior to the voyage, so as to risky maneuvers and specify the navigational actions to be taken in specific situations. While at sea a significant proportion of the activities of the navigators are directed towards controlling and adjusting the execution of the plan.

2.2 The crew and the bridge layout

The constellation of the manning of the bridge — the watch arrangement — varies according to the complexity of the navigation to be performed. In the current study the watch crew navigated the vessel through the narrow and trafficked channel leading up to Southampton harbor and, due to the complexity of the task, all four members of the bridge crew were on duty. In the following the members of the crew will be referred to by the function or role they were filling rather then being addressed by their title or rank. The roles within the four person watch arrangement are: the navigator (captain), the officer of the watch (chief officer), the plotter (first officer), and the helmsman (second officer).

Traditionally, watch arrangements have been structured in extremely hierarchical ways, and even though this has changed somewhat in recent years, the navigator is still the supreme commander of the watch arrangement. While the trend in modern crew management encourages the breakdown of the traditional hierarchy in the watch arrangement and all individual actors perform indispensable functions, no actions directly affecting the movements of the ship are taken if not ordered or ok'ed by the navigator, who in fact himself has hands-on control of the engine telegraph determining the speed of the ship.

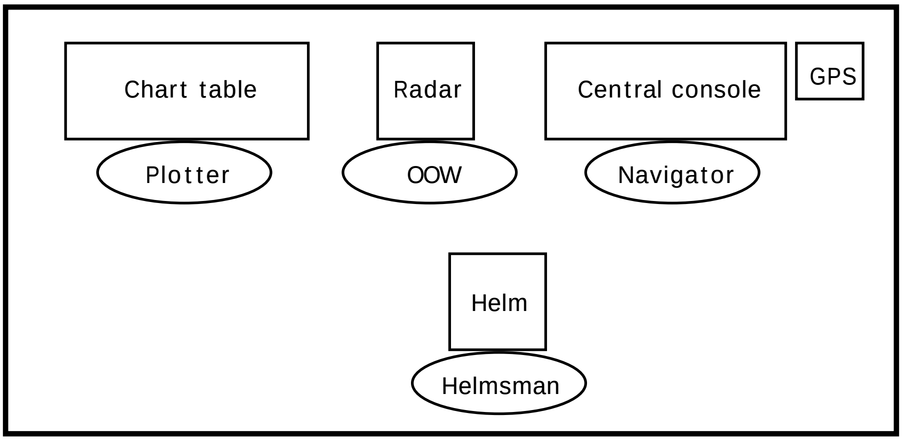

Figure 2: The bridge layout indicating the positions of the crew members (circles) and the main instruments (squares).

The navigator most often will be standing next to the engine telegraph which is located on the central console. To the left of the navigator, having the radar as his main instrument, *the officer of watch* (OOW), is looking out for traffic, buoys and other objects of relevance to the navigator. The officer of the watch is also attending all communication external to the bridge, e.g., engine control room, pilots, tugs, harbor authorities etc. *The plotter* is located at the chart table. His main task is to regularly plot the position of the ship on the sea chart. If a deviation between the planned and the actual course is detected, the navigator will be notified in order to bring the ship back on course. While the navigator has command over the rudder, it is *the helmsman* who executes the commands; it is he who turns the wheel when a helm order is given by the navigator. All orders are cried out and most of the communication (observations, warnings etc.) is done orally, thus allowing the actors to assess the intentions and monitor the actions of their colleagues.

The helmsman operates the rudder, both manually and through the auto pilot, thus executing helm orders given by the navigator. Helm orders can be divided into two categories: rudder commands and heading commands. Rudder commands are performed over a short time span and require only one reactive action — an adjustment of the rudder angle — whereas a heading command is often performed over a relatively long time span and will require multiple actions — ongoing adjustments of the rudder — in response to changing conditions.

In the case of rudder commands the communication between the navigator and the helmsman is well defined both in regard to phraseology and information flow. For example: The navigator gives the helm order 'Starboard one zero' (read: 'Starboard ten degrees'); the helmsman responds 'starboard one zero' and turns the wheel to the ordered position. The rudder starts moving and when it has arrived at the desired angle (this information is available to the helmsman on a rudder angle indicator), the helmsman gives his final report to the navigator 'Helm is one zero starboard'. Table 1 shows some of the most commonly used rudder commands and the corresponding reactions of the helmsman.

Navigator's helm order	**Helmsman's reply**	**Helmsman's action**	**Helmsman's final report**
Starboard one zero	Starboard one zero	Turns the wheel to ten degrees starboard	Helm is one zero degrees starboard
Amidships	Amidships	Turns the wheel to amidships	Helm is amidships
Hard a-port	Hard a-port	Turns the wheel hard a-port	Helm is hard a-port

Table 1: Examples of rudder commands and the associated replies, actions and reports.

In contrast to rudder commands, heading commands require the attention of the helmsman over a longer period of time. 'Steady' is a frequently used heading command meaning hold the ship on the current course, e.g. 272 degrees, until further notice. Having been given the helm order 'Steady', the helmsman has been given the command of the rudder and is expected to make adjustments of the rudder in response to deviations from the course.

Navigator's helm order	**Helmsman's reply**	**Helmsman's action**	**Helmsman's report**
Steady on 272	Steady 272	Makes necessary adjustments of the rudder to keep the ship on course 272	Notifies the navigator only in case of significant deviations from the current course
Steady at the tower	Steady at the light tower	Makes necessary adjustments of the rudder to keep the ship heading for the light tower	Notifies the navigator only in case of significant deviations from the current course
Steady rate 15 degrees	Steady rate 15 degrees	Makes necessary adjustments of the rudder to keep the ship turning at rate 15 degrees/minute	Notifies the navigator only in case of significant deviations from the current rate-of-turn

Table 2: Examples of heading commands and the associated replies, actions and reports.

In this context, it is important to notice that even when excluding uncontrollable forces like wind and current regular adjustment of the rudder is still required to keep the ship steady due to the fact that the aft of the ship will always pull slightly to the same side as the propeller is turning. In real life, though, the major threats to safe navigation come from wind and current which are at times both strong and shifting calling for timely and skilled navigation, as outlined in the following example: a ninety degree change of course in a narrow and trafficked channel.

2.3 Navigation: An example

To ensure the maneuverability of the ship, it is crucial to enter a curve at optimal speed. Generally, if the speed is too low forces like wind and current will control the movements of the ship, whereas entering a curve at too high speed will result in drift forcing the ship out of the desired curve. Hence optimal speed equals the optimal trade-off between drift and effect of the rudder. The trade-off is made by the navigator who decides at what speed to enter a curve.

About one nautical mile prior to the planned wheel-over point, the plotter starts a verbal count-down, thus directing the navigator's attention to the fact that a major change of course is coming up. The plotter repeats the notification after half a mile, immediately before the wheel-over point, and finally when the ship is in the actual wheel-over point. The navigator responds to the first three parts of the count down with ok's whereas he initiates the turn by a rudder command at the plotter's final report. If a heading command is given, it is not done until the ship has reached the desired rate-of-turn (in this case 20 degrees per minute). In the current case the helm's order is given.

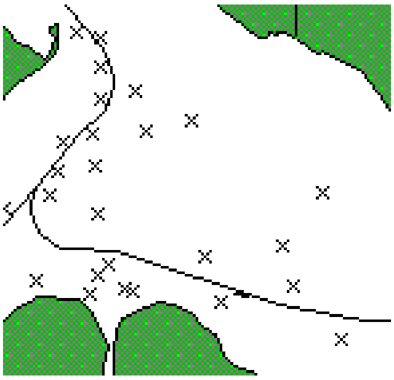

Figure 3: The first two curves in the channel leading up to Southampton harbor. The line indicated the planned course; crosses equals buoys.

Granted that the effect of the rudder is closely related to the speed of the ship, there is a tight cooperative coupling between the navigator who controls the propeller, the helmsman who controls the rudder, and the plotter who makes ongoing comparisons between the desired and the actual course. Warnings will be given by the helmsman if control over the turn rate is lost and from the plotter if the position of the ship indicated that she is off course.

Now, shortly after the heading command is given, the turn rate does in fact start falling and after realizing that it is not just a fluctuation the helmsman reports to the navigator 'Turn rate is 17 and dropping'. The navigator responds 'OK, we are currently at half speed. I'll increase the speed a bit'. In the present situation the navigator could have chosen to resume control over the rudder by giving a rudder command, but instead he acknowledges the falling turn rate and assists the helmsman in getting the ship back on a turn rate of 20 degrees by increasing the power of the engine and thereby the effect of the rudder, while leaving the control of the rudder with the helmsman.

The plotter monitors the communication between the helmsman and the navigator and starts plotting the position of the ship to determine the effect of the decreased turn rate: Is there a deviation from the planned course?

At this point, immediately after the navigator has responded to the falling turn rate, Southampton Radio broadcasts a navigational warning about a drifting destroyer positioned somewhere up the channel. Normally it would be the responsibility of the plotter to note the coordinates of the destroyer and to mark its position on the sea chart. However, the officer of the watch is aware of the fact that the plotter is presently working on plotting the position of own-ship, so he writes down the coordinates of the destroyer and leaves the paper on the chart table. The plotting of own-ship's position then reported to the navigator; the ship is currently only a ship-width east of the planned course. Hereafter the plotter starts calculating the position of the drifting destroyer, closely monitored by the officer of the watch who is awaiting the result. When the position of the destroyer is marked, the plotter points it out to the officer of the watch who then turns to the navigator and points out the destroyer on the radar, noting that no changes to the plan is currently needed. Meanwhile the ship has been brought back on course at the right turn rate. About one ship-length before ending the curve, the navigator resumes control of the rudder by giving the helm order 'Amidships' that will lead the ship on to the following course segment.

Due to the falling turn rate the navigator is a bit uncertain as to whether the drift has brought the ship too close to the coast on the port side. After finishing the turn, he asks the officer of the watch to check the next port side buoy. The officer of the watch checks the radar and responds 'Next port side buoy is right ahead, a little less than a mile'. The communication between the navigator and the officer of the watch has been overheard by the other crew members, and shortly after the plotter point out the window and says that he can now see the next port side buoy. The officer of the watch compares this 'visual position' with the radar. After ensuring that the buoy identified visually and the buoy pointed out on the radar are identical, the officer of the watch walks to the GPS, points out the buoy there and informs the navigator of the position of the next port side buoy. They were in fact a bit far to the port side in the lane and therefore started taking action to cope with this.

The current setting is characterized by a particular blend of constraints and affordances which are skillfully exploited by the members of the crew. For example, by virtue of the ephemeral nature of the medium (oral radio message), the navigational warning could easily have been disregarded or forgotten because the plotter's attention was directed elsewhere. Such problems were averted, however, because (a) the officer of the watch could overhear the message and (b) due to their proximity the officer of the watch could easily monitor the plotter and thereby knew that he was occupied with other important business. This incident is of course quite mundane but it clearly illustrates that even seemingly insignificant changes to the technology (for instance, radio headsets instead of loudspeakers) may have dire consequences in time-critical settings such as the one described here where mutual awareness between actors is essential.

2.4 Preliminary analysis

The overall objective of navigation can be seen as bringing a ship from one point to another while satisfying the given constraints of safety, time, and resources (e.g., fuel economy). In order to achieve this the watch arrangement aims at continuously developing a detailed and coherent picture of the state of affairs, i.e., an accurate picture of the performance of the ship (speed, heading, drift, rate of turn, etc.), of the position of the ship, and of the external conditions (other ships, ship traffic services, tugs, wind, current, etc.). This picture of the state of affairs serves as a basis for planning and maneuvering. Furthermore, since the task of navigation here — unavoidably — is divided among multiple actors, the development of this picture of the state of affairs is a cooperative effort that requires the actors to be mutually aware of each other's actions and to inform each other of their observations and actions.

To discuss this in more detail, it is useful to distinguish between the following categories of activities: (i) monitoring the state of affairs; (ii) planning for future action; (iii) deciding on navigation actions. Since the watch arrangement is a cooperative effort, two distinct categories of coordinative activity must be considered as well: (iv) distributing information, both within the watch arrangement and to external actors; and (v) monitoring other crew members' activities.

Monitoring the state of affairs involves all crew members. These activities comprise looking out the windows, monitoring the radar and GPS, studying the sea charts, and monitoring the other instruments. A very important 'secondary' activity in this context is what we could call cross-checking or comparison of information obtained from the different media: information achieved from one source (e.g., the view from the windows) is cross-checked by relating it to the information available from the other source (chart, radar, and GPS). The cross-checking is ideally done in-between and across all available information sources. An example of this cross-checking is the activities and communication related to the identification of the next port side buoy in the example above.

Planning for future actions: Before starting a tour, all crew members were informed about the initial plan, i.e., planned speed, courses, wheel-over points, turn rates, etc. Re-planning is done frequently due to changes in the weather conditions and other external events. The re-planning is mainly done through a discussion between the navigator and the officer of watch. The other crew members can overhear these discussion and will some times comment on or suggest changes to the new plan. During this process the navigator or the officer of the watch will request information from the plotter concerning, for example, depths, potential grounding risks, lane separation, etc. Again these request and replies can be heard by all members of the watch arrangement.

Deciding on navigation actions: Decisions like when to change the rudder angel or how much to turn it must be taken on the basis of knowledge of the current performance of the ship and the external conditions. Again, the decisions are mainly taken by the navigator supported by and discussed with the officer of the watch in close collaboration with other crew members. Action concerning the rudder is implemented by the helmsman, and actions concerning the engine will some times be implemented by the officer of watch. All commands or acknowledgments are cried out loud.

Distributing information: All crew members take part in the distribution of information. Usually this is done orally, e.g., the navigator's describing his intentions for the next ten minutes of maneuvering, the navigator's rudder and engine requests and the related replies from the officer of the watch or the helmsman, and the plotter's counting down to the next wheel-over point. Information distribution can also be external: The officer of the watch will call the vessel traffic service and inform them that the ship has passed a certain point, or call up another ship and inform of the intentions for the following maneuvers. In addition to the oral distribution of information the actors direct the attention of their colleagues to certain aspects by pointing at them or, less obtrusively but more immutably, by writing a note and placing it at a place where the relevant crew member can see it, cf. the officer of the watch writing down the position of the drifting destroyer in the incident described above.

Monitoring the other crew members: By observing the navigator's commands to the helmsman the other watch arrangement members keep track of what goes on, or they can be aware of the fact that, for example, the plotter is so busy that he needs support. Again, the (in-visible) actions accomplished in order to fulfill this function involves all the actors on the bridge.

3. Analyzing the social organization of work

How can we approach the analysis of the cooperative aspects of complex human-machine systems such as the one described above in a systematic way?

The cooperative work arrangement and the common field of work: First of all, we propose to conceive of cooperative work as defined by actors' being mutually interdependent in their work in the sense that one actor's change to the state of a common field of work (or action to prevent change, if that is needed) affects the situation facing the others, and vice versa (Schmidt, 1991; Schmidt, 1994). Their interdependence is constituted by the interdependencies between the objects and processes constituting the field of work. That is, in line with the human-machine systems approach's basic distinction between a human component and a technical component, we distinguish between a cooperative work arrangement and a corresponding field of work. Similarly, the foundation for a systematic analysis of cooperative work is a conceptualization of the statical and dynamical characteristics of the ship.

The common field of work: What we call the field of work is not only the ship, however, but the part of the world upon which the cooperating actors work or which directly impacts on their actions: the physical environment, the sea lanes, etc. It also comprises the sensors and effectors as well as the more complex tools and control mechanisms that may have been inserted between the actors and the objects and processes as well as the various representations of the state of these objects and processes and of the control systems (gauges, displays, radar screens, VHF receivers, printouts). Finally, the field of work will comprise — in an indeterminate way — the repertoire of potential material resources and technical artifacts.

The boundary and character of the field of work may change dynamically. For example, when a ship meets another ship during its voyage, the field of work of the crew — basically, the ship and the water — 'suddenly expands to include another ship' (Perrow, 1984, p. 178). Similarly, crews face fields of work that are basically different from the one they are faced with on the open ocean

> 'when ships a city block long go into port with only two feet under their keel, with highly unpredictable suction effects and a virtual complete loss of maneuverability. [This] increases the time-dependent nature of the system and reduces the slack available (tighter coupling), and through increased proximity, brings into play poorly understood processes (the suction and bank effects), which rely upon indirect and inferential information sources (thus, more complex interactions are fostered).' (Perrow, 1984, p. 182).

The interdependence constituted by the common field of work is of varying complexity in the objective sense that the complexity of a system is a function of the number of possible states the system may have, in part as a result of interactions among its elements.

The complexity of the field of work will depend on, for instance:

- The number of interacting elements.
- The heterogeneity of the elements.
- The heterogeneity of the relationships/interactions between elements..
- The rate of spontaneous changes in the field of work.
- The rate of propagation of state changes/interactions among elements of the system (the degree of coupling).
- The field of work's reactivity to induced changes.
- The irreversibility of induced changes (also, cost of reversing induced changes).
- Inadequacy of representations of the state of (parts of) the field of work (latency, invisibility, distortions).
- Inadequacy of effectors with respect to the state of (parts of) the system (sluggishness, weakness, distortions).
- The degree of freedom offered by effectors.

The cooperative work arrangement: By involving multiple actors, cooperative work is inherently and inexorably distributed. No agent is all-knowing and all-powerful. Actors must act and interact on the basis of partial knowledge and are, accordingly, partially autonomous in their work.

With many complexly interdependent actors and many possible states of the field of work (due to many interacting elements and processes), the cooperative effort will become 'as densely tangled as a plate of spaghetti' and it thus risks to 'trash around chaotically' (Waldrop, 1992, p. 109).

What prevents this from happening? Several strategies are (observably) possible:

(1) The degrees of freedom of actors may be constrained by the physical form of the field of work. In the design of the field of work, wise designers will try to eliminate unnecessary interactions between elements of the field of work ('decoupling', in systems theory), and in the design of the work organization one will try to restrict the space of possibilities of the individual actor.

(2) Timely and adequate visibility of the (state of the) field of work may allow actors monitor the state of the field of work beyond the scope of their own immediate responsibilities so as to be able to anticipate system states which demand certain interventions and may thus prevent the system as a whole from 'gyrating' or 'trashing around chaotically', for instance due to delayed intervention (i.e., positive feedback), or due to erroneous interventions.

(3) Ensuring that the structure of the cooperative work arrangement matches that of the field of work reduces interdependencies among actors (in terms of the degree of coupling and the frequency of interactions).

(4) Beyond the scope of these strategies, 'articulation work' counters the distributed nature of cooperative work. Normally, the myriad interdependent and yet distributed activities must be coordinated, aligned, meshed, etc., in short, *articulated.* The obvious and fundamental way to do that is to facilitate mutual awareness among actors, for instance, by having actors working in the same room or by providing some multi-media emulation of a 'shared space'. Mutual awareness enables actors to mutually align their individual behavior so that the number of *likely* states of the system is reduced. Mutual awareness among actors is 'low cost' way of countering distributedness (for instance, broadcast information does not interrupt ongoing activities or demand a reply). However, task interdependencies are often of an order of complexity where the provision of facilities for mutual awareness and ad hoc interactions is insufficient. Other means are required to make task interdependencies tractable, e.g., coordination mechanisms (Schmidt and Simone, 1996).

In the articulation of interdependent and yet distributed activities, a limited number of salient modes of interaction can be abstracted:

(a) Unobtrusive versus obtrusive: Interactions can be more or less obtrusive: some interactional activities such as pointing or tapping at an item or talking or shouting to colleagues are be highly intrusive in that they impose an obligation on the others to notice and react accordingly (more or less instantly). They therefore disrupt current activities (which may or may not be appropriate). Other interactional activities can be quite inconspicuous, such as, for example, embedding cues, humming, gazing, thinking aloud, leaving traces.

(b) Embedded versus symbolic: Embedding cues by highlighting particular items belonging to the field of work or representing the field of work, for instance by positioning them in conspicuous ways, at unusual locations or in abnormal orientations, by marking them etc., has significant advantages in that it (i) uses items that are ready-at-hand, perhaps ubiquitous, and that are constantly monitored due to their status as belonging to the field of work and (ii) therefore is more efficient and less intrusive and distracting than, for instance, pointing or talking or other interactional activities that impose the role of a recipient on somebody.

Embedding cues in objects, for example by marking a certain feature in the field of work so as to convey to others that they should pay attention to a particular occurrence or take a particular action, is not, strictly speaking, a symbolic act. We are here following Peirce's distinctions:

> 'In respect to their relations to their dynamic objects, I divide signs into Icons, Indices, and Symbols […]. I define an Icon as a sign which is determined by its dynamic object by virtue of its own internal nature. […] I define an Index as a sign determined by its dynamic object by virtue of being in a real relation to it. […] I define a Symbol as a sign which is determined by its dynamic object only in the sense that it will be so interpreted.' (Peirce, 1901)

Thus, an artifact 'determined' by the field of work can be conceived of as having the function of an *index*: objects belonging to the field of work, means of data acquisition (e.g., sensors), representations that map the state of the field of work automatically (e.g., gauges, radar) or are made to represent the state of the field of work (e.g., the updated charts).

The primary function of, for example, the annotated chart is that of a representation of the state of the field of work. The chart does not have the abstract nature that provides the degrees of freedom in its manipulation that otherwise makes *symbolic* representations so powerful. The chart should rather be seen as a *index* of a particular section of the environment in the sense of a mapping. The repertoire of allowed operations on the chart is strictly limited by this primary function. Any modulation of the way in which a chart is manipulated is therefore a sign embedded in the appearance of an artifact which is standing proxy for the state of the field of work. That is, the message is cloaked.

Interacting by manipulating some object or system belonging to or in an indexical relation to the field of work is a restricted way of interacting: The bandwith of embedded cues is limited to the degree of freedom offered by the role of the object in the field of work; the turn-around time of embedded cues may be limited by the frequency of state changes in the field of work; and the message is garbled in that it is shrouded in the state of an object belonging to the field of work or representing certain features of the field of work.

(c) Ephemeral versus persistent: A wide range of interactional activities are ephemeral in the sense that articulation work in these modes only exist in the flux of unfolding activities. For example,

- monitoring the activities of others, by seeing and hearing what the others are doing, where they are in the room; by noticing the level of letters in the in-box or the lack of certain parts in racks containing the buffer stock and so on;
- making one’s own activities publicly visible by modulating operations on the field of work, humming, thinking aloud;
- directing attention by modulating work activities in uncommon, unusual, or abnormal ways, by humming, drumming, coughing, gazing, pointing, nodding, talking, shouting.
- allocating tasks by pointing, nodding, talking, shouting.

As soon as the articulation activities have been carried out and a new situation has arisen, the articulation that was achieved vanishes without trace, as it were — like the snows of yesteryear.

In important ways, the same applies to interactional activities that involve embedding cues. While certainly based on the use of artifacts, embedding cues depend on the fate of the items conveying the cues in the ever-changing field of work. The embedded cues may be erased by state changes, or they may not. As vehicles of embedded cues, the highlighted objects live an uncertain life.

Because of the immediate feedback and the ensuing possibilities of detecting and recovering from misunderstanding, combined with expressive power provided by the vast repertoire of modes that can be combined at any time, these modes of articulation offer immense flexibility in terms of articulating activities in face of the mundane and dramatic contingencies of cooperative work.

These interactional modalities are especially crucial in cooperative work settings where articulation work is time-critical, as in the case of maritime navigation. Articulating cooperative activities in such settings typically requires a permanently open channel of communication with minimal turnaround time, for example by having the operators in the same room at the same time, so as to allow them to convey the multitude of inconspicuous cues that are required for cooperators to acquire and maintain reciprocal and general awareness of the changing state of affairs within the cooperating ensemble, as well as the field of work at large. Likewise, articulation of distributed activities that involve discretionary decision making — for instance planning a new route — will typically require, at least intermittently, various negotiation processes. For this purpose, co-located ‘face-to-face’ interactions provide the required large bandwith, not only in terms of gigabits per second but also, and more importantly, in terms of a rich variety of interactional modes with powerful and flexible social connotations.

On the other hand, however, these ephemeral interactional activities do not provide strong support for making decisions and commitments concerning the articulation of cooperative work accessible to the members of the cooperating ensemble, independently of the situation, and independently of particular individuals or for supporting the development and implementation of stipulations for the ways in which in which cooperative work is to be conducted and articulated.

Written records (log books, recordings, minutes, memos etc.) provide persistence to decisions and commitments made in the course of articulation work: ‘The written language [reaches] back in time’ (Goody, 1987, p 280). Written records are, in principle, accessible to any member of the ensemble, whatever its size and distribution in time and space. ‘Written systems can provide a larger number of people with the same information at one time.’ ‘Written messages are portable, allowing interaction without spatial constraints.’ On the other hand, 'Written systems are much less dependent on physical arrangements' and 'less time-dependent than oral systems.' (Stinchcombe, 1974, pp. 50 f.).

Written artifacts can at any time be mobilized as a referential for clarifying ambiguities and settling disputes: 'while interpretations vary, the word itself remains as it always was. (Though every reading is different, it is a misleading exaggeration of the literary critic to say that the text exists only in communication.)' (Goody, 1986, p. 6). However, 'written language is partly cut off from the context that face-to-face communication gives to speech, a context that uses multiple channels, not only the purely linguistic one, and which is therefore more contextualized, less abstract, less formal, in content as in form.' (Goody, 1987, p. 287).

4. Conclusion

Based on some preliminary results from a field study of time-critical cooperative work within the domain of ship navigation we have discussed some methodological problems of work analysis in such domains with the purpose of discussing potential computer-based support of aspects of the work. The research is still in an initial phase, and we have probably raised more questions than we have answered.

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