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Workload and navigational control

The control levels of COCOM as framework for ship bridge HMI design

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***Abstract*—A future sustainable world will also rely of safe, efficient and environmentally friendly maritime transportation. This paper suggests a new way of looking at ship bridge design based on some theoretical constructs of information processing and cognitive engineering. It briefly references two maritime accidents where a mismatch between the availability of information and human performance can be detected. It then shortly discuss the impact of stress on human performance and present how Hollnagel's Contextual Control Model (COCOM) theory can be used to structure design work and bridge layout based on operator workload. The intention is to advance HMI design and integration of bridge equipment based on the different theoretical control levels. The *Scrambled* control level is presently not supported by modern bridge equipment and new research into this type of user interfaces is proposed.**

***Keywords*—control room design; navigation; ship bridge; COCOM**

I. INTRODUCTION

Around 90 percent of the world's trade is carried on ships [1]. Effective, safe and environmentally friendly shipping is important as we head into future unknown waters of increasing population, changing climate with more extreme weather and higher demands on emission reductions. Shipping is an industry with longstanding traditions. Previously, information available on the deck of a sailing vessel or on a steam ship bridge was limited, to a few coarse instruments and often only rules of thumb learned through experience. Today we have a plethora of information available. And more is coming. In 2006, the International Maritime Organization (IMO) started working on a concept termed *e-Navigation* to "harmonize the collection, integration, exchange, presentation and analysis of marine information onboard and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment" [2].

It is little doubt, that important environmental data available onboard in real-time will enhance the safety of shipping. Weather reports has already for decades been transmitted to ships within range of coastal stations and helped ships escape bad weather, as compared to having only barometers and knowledge of the general paths weather systems. Today nautical chart updates are transmitted to ships by satellite connection whenever fairways are changed or new shoals are detected. e-Navigation will not only enhance knowledge onboard and increase safety and efficiency, but also support a sustainable future industry. The new enhanced information flows will be available through a number of *Maritime Service Portfolios* where it will be structured and standardized for easy access. However, one problem that must be taken seriously is where and how to display all this new information to support the human operator on the bridge. Let us therefor briefly start out by look at the work situation on the bridge today.

II. DECISION-MAKING ON THE SHIP'S BRIDGE

Modern oceangoing cargo ships of larger size usually have four bridge officers responsible for the navigation of the ship. The captain has the overall responsibility of the ship and is often not watch-going under normal circumstances. The other three officers are working on a round-the-clock schedule. During daylight, the watch officer is usually alone on the bridge in open sea conditions. The work consist of monitoring course keeping and the surroundings, looking out for other ships or dangers. This is done by binoculars, chart and radar. On the Electronic Chart and Display Information System (ECDIS) other ships equipped with an Automatic Identification System (AIS) transponder will be visible when within radio range. Besides position, course and speed, the AIS will show other information such as name and destination.

This is the case for larger ships, but smaller vessels like fishing and leisure crafts might not carry AIS and will only be visible on the radar. There are of course a plethora of other tasks such as recording position fixes and documenting the voyage, but generally, during ocean passages, the workload of the watch officer can be very low. With no ships around and nothing on the radar screen for 24 nautical miles around, the problem might instead be one of boredom (low arousal). During darkness, a seaman is added to the bridge as a lookout, both because the degraded visibility puts higher demands on vigilance, but also as a safeguard against the officer falling asleep.

As the ship is approaching its destination and entering coastal waters the traffic intensity may increase, buoyage systems that needs to be found and traffic separations adhered to. This puts higher demands on the human on the bridge. More observations needs to be made and more decisions taken during a given time interval. The workload has now increased compared to the open ocean situation.

As the ship is approaching port, the workload increases even more. Radio contact needs to be taken with the pilot station and pilots picked up off the coast. During the approach through a complicated archipelago, great concern needs to be given the charts and other vessels in the area, communication may need to be made with various stakeholders in port to prepare for the arrival, and rigorous time keeping in navigation exercised to arrive in time for tugboats and linesmen. Often this increased workload is mitigated by adding more persons to the bridge team, e.g. the maritime pilot and maybe an extra officer.

Finally, the ship arrives in port. The workload on the bridge now increases even more. The traffic in a busy port maybe heavy, a lot attention need to be spent on maneuvering with wind and current now affecting the slow moving vessel. Mooring lines needs to be prepared and a thousand tasks preformed. The workload is very high and the captain also joins the bridge team, often doing the final maneuvering to berth.

But of course, workload might peak at any time due to unforeseen circumstances, which will be illustrated later on.

The diagram in Figure 1 tries to schematically describe the general workload of a bridge officer as the quota between resources demanded (both cognitive and physical such as attention and time) and resources supplied. To the left in the figure we can see that the resources demanded during an ocean passage are generally low and then increases as the ship enters coastal waters and finally the confined waters of the archipelago and the port. We can also see that there for an individual is a maximum level of resources available, due to e.g. skills and experience. This maximum level might shift between individuals, but may also shift within one individual due to e.g. fatigue or drug use. (The diagram is, of course, only a very general description and may differ widely for any particular voyage.)

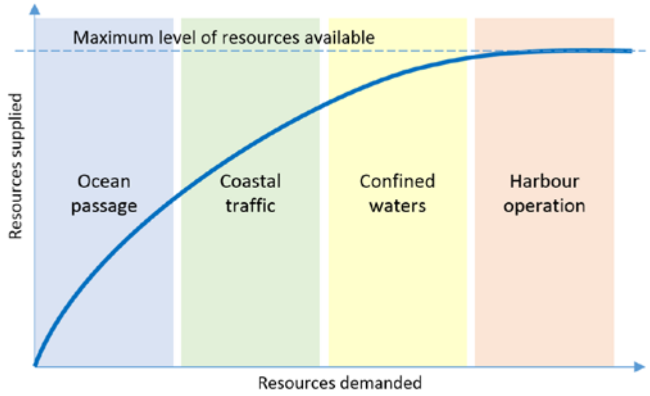

Fig. 1. The diagram shows the relationship between resource demand and supply during typical phases of a ship’s voyage. Resources are here both cognitive and physical and can be supplied by higher arousal (up to a certain limit), by automation or by adding another operator. Adapted after [3].

In the model above, we can see the resource demand on the bridge changes during different phases of a normal voyage. Changing demands on workload can be dealt with on an individual level by increased or decreased arousal, but may also, as mentioned above, be dealt with by adding more personal to the bridge team. However, in abnormal circumstances the situation will have to be handled with the resources available at the bridge at the time of the incident. We now need to take a closer look at human operator.

III. ACCIDENTS AND WORKLOAD

I will illustrate the workload of bridge officers by briefly telling the story of two ship accidents.

A. The Sleipner accident

In 1999, the high speed ferry *Sleipner* crashed into a rock on the Norwegian coast and 16 of 85 passengers and crew drowned as the ferry subsequently sank. It was a dark November evening with gale winds and high waves. The ferry was underway in 35 knots over a stretch of open water. The captain and the first officer were seated in an airplane cockpit arrangement in the wheelhouse and navigating visually using the sector lights of the beacons up along the coast. Due to the sway of the vessel, the autopilot had been disengaged and the captain was steering manually using a knob on the armrest of his chair. Approaching Haarskru lighthouse, both officers independently turned to their separate radar sets making adjustments. No one was looking out the window for the white sector of the next beacon. After having adjusted his set, the first officer looked up and saw the flash from Haarskru lighthouse, but now in red sector, and on the starboard bow. He immediately realized that they were in danger of hitting a rock at the side of the fairway and called out a warning. The captain looked up and turned on the floodlight of the vessels. The rock appeared just ahead of *Sleipner* and the captain gave full port rudder and reversed the engines, but the maneuver came too late and the vessel crashed on to the rock in almost full speed [4].

One may in hindsight note that although the ferry had a fully functional, state of the art bridge, with an electronic chart system, the officers never managed to recover their situational awareness until I was too late. Although all information was available, there was simply not enough time to read all the necessary instruments and integrate them to a conclusive image of the situation.

B. The Rena accident

A night in October 2011 the 225-meter long container vessel *Rena* grounded on the Astrolabe Reef off the North Island of New Zeeland. The vessel was severely damaged but remained on the reef for several months before she finally broke up, causing environmental pollution. *Rena* was approaching the pilot pick-up station for Tauranga Port but needed to hurry because she was at the end of the tidal window allowing entry to the port. The captain decided to make a shortcut south of the planned track bringing the vessel within one nautical mile to the Astrolabe Reef. *Rena* had no electronic chart system and used paper charts placed in the chart room at the back of the bridge. The voyage was monitored by position fixes plotted with pencil on the paper chart in the chart room. As the *Rena* approach Taruranga pilot station the captain joined the second officer and the lookout on the bridge. The captain noticed an intermittent echo on the radar screen about 2.6 nautical miles dead ahead of the vessel. He and the outlook tried to detect what was causing the echo using binoculars both from the bridge and the bridge wing, but without success. As the captain went to the chart room to plot the ship's position on the chart the *Rena* struck the reef in 17 knots [5].

It is in hindsight interesting to note that part of the information needed to keep up the operators situation awareness was stored on the nautical chart placed in the chart room at the back of the bridge while the only real-time information provided, was by the radar available at the front of the bridge.

From an operator performance perspective the two accidents referred to above is very different. In the *Sleipner* case, the officers suddenly became aware of imminent danger and under influence of stress and time pressure was not able to recover the situation. In the *Rena* case, the officers were unaware of the danger and the workload remained relatively low all the way up to the grounding. But in both cases, presentation of information did not support solving the problem they were heading into. The *Sleipner* had an electronic chart system showing both the danger and the position of the vessel relative to the danger, but the chart was located in an off-view position and presented in a format that did not support immediate action. On the bridge of *Rena* information was fragmented in two different locations and needed to be "carried in the head" between the chart room and the radar in order to integrate it into a solution that made the problem transparent.

It is interesting to reflect on the workload situation of the officers just prior to the accidents when recovery would still have been possible. Stress decreases the ability to receive and process information (cognitive tunneling and lower working memory capacity). Stressors affect the efficiency of information processing generally by degrading performance [6]. Many of the effects are mediated by arousal. Physiological arousal can be objectively measures through indicators such as hart rate, pupil diameter and hormonal chemistry [7]. The importance of physiological arousal is indicated by the inverted U function of performance, often referred to as the Yerkes-Dodson law [8]. See Figure 2.

The figure shows that performance is generally low with low arousal then slowly increases towards an optimum level of performance as the level of arousal increases, and then subsequently performance declines as stress induced arousal increases further. This is the reduced performance we can see under heavy stress, as in the *Sleipner* case. But we can also see the difference between the two curves of complex and simple tasks. Simple tasks can still be performed under heavier stress that complex tasks. This might be due to less demand on cognitive resources. This suggests that information necessary for imminent decision-making should be presented in a less demanding form.

Before we return to *Sleipner* and *Rena* and our final goal to say something about information display and bridge design, we will make a brief reference to the theoretical framework of Hollnagel's Contextual control model.

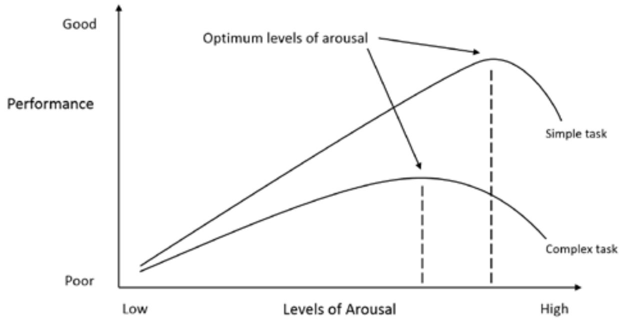

Fig. 2. The Yerkes-Dodson law showing the relation between level of arousal (stress) and performance. Optemum performance require a certain level of stress, but too little, or too high, arousal is not good. The optimum level of performance is obtained at higher level of stress for simple tasks [7].

IV. THE CONTEXTUAL CONTROL MODEL

The Danish psychologist Erik Hollnagel 1993, developed the cyclic Contextual control model as a response to the fragmented classical stimulus-response based human-machine view [9]. This model depicts human actions, as the result of the context they work in and feedback from earlier actions, but their activities is also the result of feedforward, expectations based on their current understanding of the situation, thus becoming a spiral of steps in a "joint cognitive system" of man and artifacts. See Figure 3.

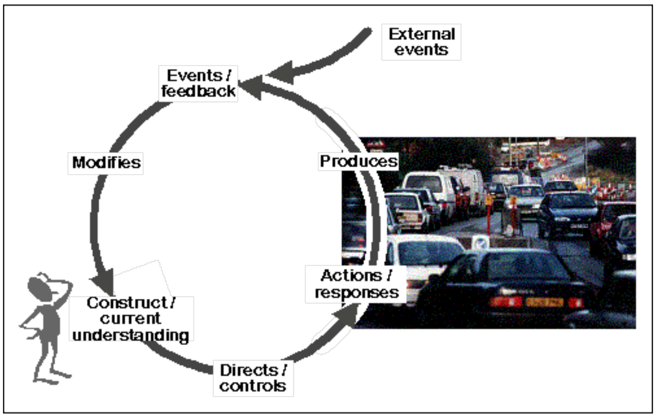

Fig. 3. Hollnagels cyclical Contextual control model (COCOM) [10]

An important feature of COCOM is the *control modes*, which corresponds to "characteristic differences in the orderliness of performance" [11]. If we as the system take all involved parts of the navigation task of a ship, we can talk about the control levels of the joint system. The four control modes Hollnagel suggests are: Strategic, Tactical Opportunistic and Scrambled. Hollnagel writes that they should be considered as regions on a continuum, which ranges from no control, to completely deterministic performance. Hollnagel describes these control levels as follows:

A. Strategic Control Mode

In the strategic control mode, the joint system has a wider time horizon and can look ahead at higher-level goals. The dominant features of the situation or the interface therefore have less influence on the choice of action. At the strategic level the functional dependencies between task steps and the interaction between multiple goals will also be taken into account in planning [11].

B. Tactical Control Mode

The tactical control mode corresponds to situations where performance more or less follows a known procedure or rule. The joint system's time horizon goes beyond the dominant needs of the present, but planning is of limited scope or range and the needs taken into account may sometimes be ad hoc [11].

C. Opportunistic Control Mode

In the opportunistic control mode, the salient features of the current context determine the next action. Planning or anticipation are limited, perhaps because the context is not clearly understood or because there is limited time available. Opportunistic control is a heuristic that is applied when the constructs are inadequate, either due to lack of competence, an unusual state of the environment, or detrimental working conditions. The resulting choice of actions is often inefficient, leading to many useless attempts being made [11].

D. Scrambled Control Mode

Finally, in the scrambled control mode, For humans there is little, if any, reflection or cognition involved but rather a blind trial-and-error type of performance. This is typically the case when situation assessment is deficient or paralyzed and there accordingly is little or no correspondence between the situation and the actions. The scrambled control mode includes the extreme situation of zero control [11].

In the perspective of the work situation of the officers on the ship bridge, Hollnagel's control model can be used to structure the information environment so that it might fit different time constraints and workload situations of the operators, different resource demands and stress levels. Such a structure might be helpful for interaction designers when designing the new information environment for e-Navigation during in the coming years.

V. CONTEXTUAL CONTROL LEVELS ON THE SHIP'S BRIDGE

How can we use the four contextual control levels when working with bridge design? And do we already accommodate these four control levels in the bridge design we have today? In the case of *Sleipner* and *Rena* for example? Let's go through the four modes one by one.

A. Strategic Control Level

Modern bridge procedures and bridge design often well support the Strategic level of control. Voyage planning is done ahead of departure in the relative calm of the chart room or chart table at the back end of the bridge. Here is where you will find the tables, literature and charts needed for careful planning. Several alternative route choices can be compared without time stress. On a modern bridge, you will find an ECDIS planning station and a computer able to go online and receive information and updates from costal administrations and port authorities. This is also the place where strategic planning can be conducted during long ocean passages. Abundant available time also lessens the demands on information design. If information is not understood the first time, there is time to read or look again, or ask for advice. In the diagram in Figure 4 where the control levels are placed on top of the resource diagram presented earlier, the Strategic control level is typically placed to the left, e.g. during passage planning in port, or during ocean passage, with low resource demands.

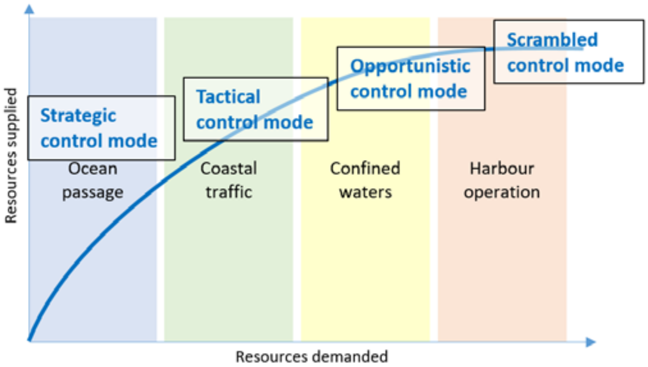

Fig. 4. The same diagram as in Figure 2, but with Hollnagel's four contextual control levels overlaid on the different phases of the voyage.

B. Tactical Control Level

On the front of a modern ship bridge, you might find an Integrated Navigation System with several screens on which ECDIS, radars and conning are displayed, as well as other possible services. If the bridge has a pilot, co-pilot design, you will find two chairs for the watch officer and a co-officer. Although there are several problems with the interaction and information design of radar and ECDIS equipment, they all fairly well support the navigators on the tactical control level, typically illustrated in Figure 4 by the coastal water phase of a voyage. Bridge officers here work with a just-enough-time constraint and needs decision support to be clear and unambiguous. Traditionally anti-grounding and anti-collision is taught as two different tasks at the nautical academies, and also supported by two different instruments, the ECDIS and the radar. The problem here is one of integration, just as it was for the officers on *Rena*. Except that they did not only need to integrate information from two screens, they had to walk between the chart room and the radar screen.

C. Opportunistic control level

As mentioned, the problem in the *Rena* case was that information about the submerged reef was not available on the radar screen. Apart from an occasional breaking wave that showed up as an echo. If Rena had had a modern integrated chart-radar with the nautical chart as an underlay on the radar screen the solution to the mysterious echoes would have been obvious: the Astrolabe reef depicted by two independent sources, GPS and radar.

“Planning or anticipation are limited, perhaps because the context is not clearly understood or because there is limited time available.” Hollnagel wrote for the opportunistic control level. Integration of information will be important to support this level, and here much remains to be done. Integrating chart and radar image is a start, already available in modern systems; integrating the right e-Navigation information, without causing clutter or information overload will be the next challenge.

D. Scrambled control level

In the *Sleipner* accident, related earlier, the two bridge officers suddenly found themselves in a situation where they had temporarily lost their orientation and very few seconds to regain it. They know that they were heading for danger but did not know if the danger was to port or to starboard or straight ahead. Nor did they have the time to investigate their position relative to the danger using the ECDIS. In this Scrambled situation, we may conclude that none of the available bridge equipment managed to supply them with the necessary decision support.

Research done into navigation and chart displays has demonstrated cognitive off-loading, by removing the need for mental rotations, by presenting the chart view in an egocentric 3D projection [12]. In Figure 5 such a projection is shown on a separate “conning screen” beside the ordinary ECDIS north-up chart view. The ship is southbound and a right direction on the chart translates into a port (left) turn with the ship.

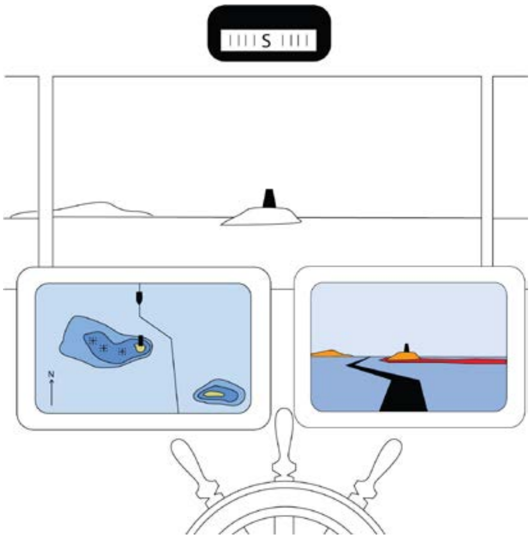

Fig. 5. The left screen shows on a traditional exocentric, north-up oriented, nautical chart how the southbound ship is approaching a dangerous rock with shoals on it western side. The helmsman now needs to turn port (left) to follow the black planned route. An action that is not allways intuetive in time stressed situations due to the mental rotations needed. The right screen shows a suggested “egocentric view” nautical chart, sutable for Scrambled control modes [12].

The cognitive offloading is obtained by showing the chart in an egocentric mode in the right display. The information is prepared and immediately available for quick decisions, such as which direction to proceed, or if there is enough water under the keel to sail. Such a projection could also be, overlaid on the widescreen as in airplane head-up display (HUD), or as augmented reality in a pair of glasses. Several research projects are presently underway using augmented reality glasses or visors for maritime use [13, 14].

VI. DISCUSSION

I am here arguing that the four control levels of COCOM can be used as a framework for discussing where and how on the ship bridge the plethora of new e-Navigation information can and should be presented. I am also arguing that we presently are missing an important facet of the human-machine interface: the information that needs to be pre-integrated and immediately available to support decision-making in “scrambled situations”. The right screen in Figure 5 shows an example of such a display where the information needed for the *Sleipner* officers to make a decision using their “gut feeling” could have been available.

To summarize this paper In Figure 6 I have made a schematic drawing of a modern ship’s bridge. To the right are the two chairs in a pilot, co-pilot bridge set-up, facing right and towards the front of the ship. In this figure, the Scrambled control mode is illustrated by two HUD displays in the windscreen in front of the two operator chairs. To the far left in Figure 6, at the aft part of the bridge, an electronic chart table is illustrating the back-bridge area where the Strategic level voyage planning takes place. Here we can afford having a high information density due to abundant time available. This is the place where most of the new e-Navigation information should be placed.

In the next section from the left in Figure 6 we have the information displays for the Tactical control level. Here illustrated with the traditional ECDIS and radar screens of a typical modern ship bridge. The separate information on each screen still has to be manually integrated in the head of the bridge officer, but we are all right because we still have adequate time available in the Tactical control mode. Some new e-Navigation information can be added to the displays without causing information overload. An example is dynamically filtered Maritime Safety Information, visible directly on the chart in a suitable format when approaching the area in question.

Second to the right in Figure 6 the Opportunistic control level has been illustrated by an integrated radar with chart underlay (or an ECDIS with radar overlay). The integrated display could be in “head-up” mode, meaning the forward-direction of the ship is up on the display, removing one component of the mental rotations needed to translate chart views to actual ship maneuvers. In some cases, this is cognitively off-loading (e.g. navigation in narrow archipelago fairways), in other situations the traditional north-up orientation is preferable (e.g. communicating with other ships in high traffic density). In this control mode, as well as in the Scrambled mode, the new e-Navigation information needs to

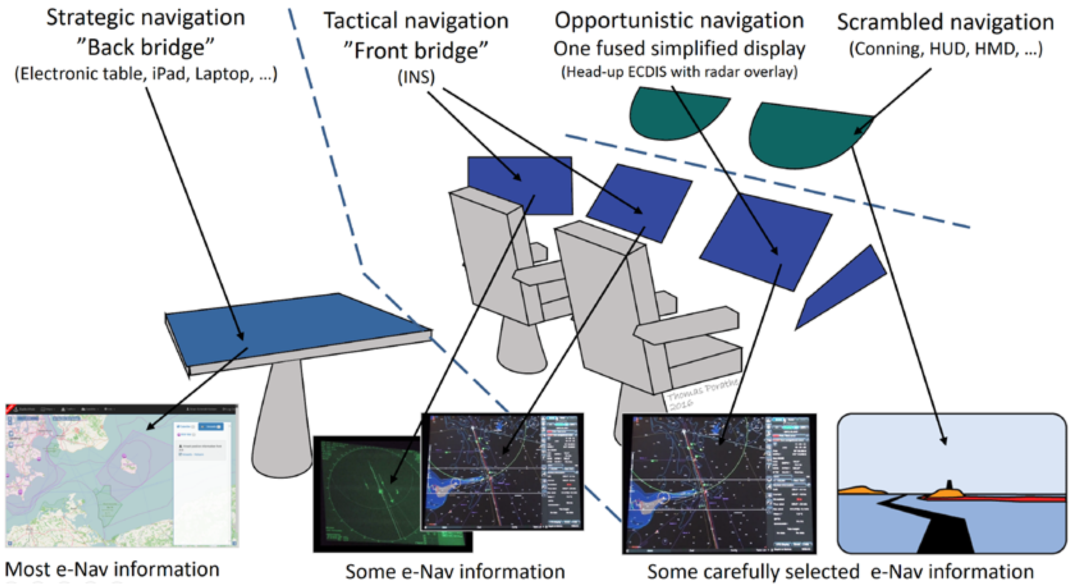

Fig. 6. The four different contextual control levels supported by different information displays and HMIs in different locations on the ship bridge (illustration by the author).

be carefully selected and prepared to be readily useful. This will be a challenge for future research and design.

VII. CONCLUSION

This paper has suggested a new way of looking at ship bridge design based on resource demands in different phases of a ship's voyage as well as the stress level and workload of the bridge operators. Hollnagel's Contextual Control Model was used as a framework and the strategic, tactical, opportunistic and scrambled control levels identified as useful abstracts for different workload levels on the bridge. The work places of the four different control levels might be at different locations on the bridge, as suggested in Figure 6.

By designing different strategic, tactical, opportunistic and scrambled ship simulator scenarios, different types of new "e-navigation equipment" could possibly be benchmarked and tested. This could prove an interesting method to support usability and human-centered design in a domain where information overload is a risk.

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