

Visualizing the Decision Space of a Ship's Maneuverability in a Real-Time 3-D Nautical Chart

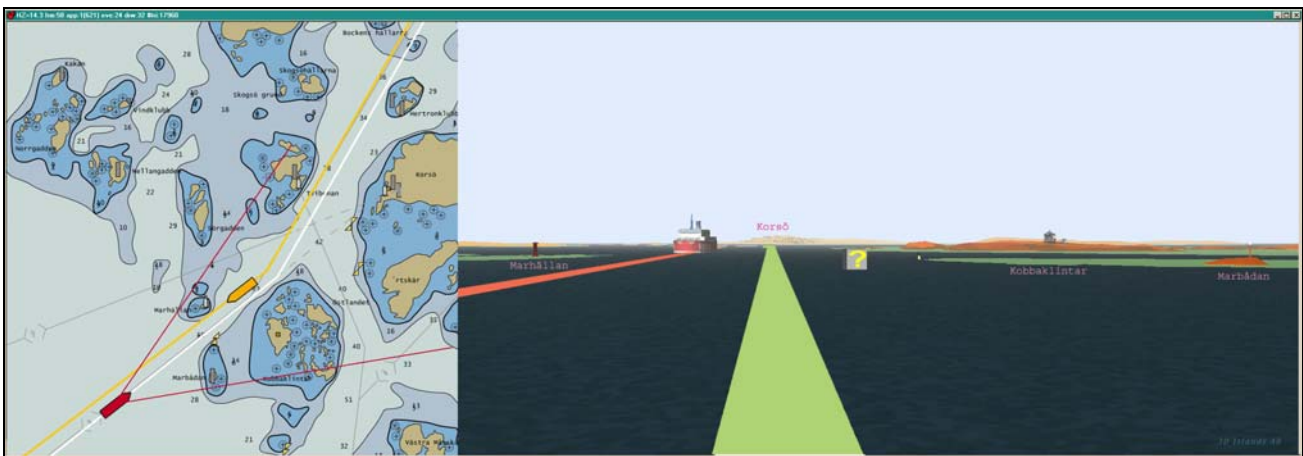
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1. SUMMARY

In an information design project at Malardalen University in Sweden a computer based 3-D chart system is designed based on human factors principles of more intuitive navigation in high speeds. This has earlier been presented at the IST-036/RWS-005 Massive Military Data Fusion and Visualisation workshop in Halden, Norway, 2002. See figure 1. In this paper, a way of visualizing the decision space of a ship's maneuverability a few minutes into the future is suggested. Known methods for calculating a vessels future position based on knowledge of present position, direction, speed and acceleration as well as internal and external forces acting on the system is used. Such a visualization tool will be best put to use on huge ships of great mass such as for example large oil tankers.



**Figure 1: 3-D Chart Based Decision Support System.
The entrance to Mariehamn in the Åland archipelago in the Baltic Sea.**

2. INTRODUCTION

The shipping industry is constantly working on improving ship structure and the reliability of ship systems in order to reduce accidents and increase efficiency and productivity. Today's ships are more technologically advanced and more reliable than ever. Still, maritime accidents happen because ship structure and system reliability are a relatively small part of the safety equation. The maritime system is a

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people system, and about 75-96% of marine casualties are caused, at least in part, by some form of human error. [1]

But human errors can be reduced through human-centered design. In an ongoing research project a decision support system for nautical navigation is designed. The system is based on an *egocentric* chart view, a *bridge eye perspective*, as opposed to the *exocentric* or *bird's eye view* of the chart presented in common electronic nautical chart displays. The chart in turn is extended with a 3-D geographical database allowing the display to show a synthetic virtual environment with navigational information layered on top. Some new concepts of the 3-D chart is the dynamic *No Go Area Polygons*, coloring areas with water too shallow for the vessel with a warning color taken into account tidal level, the ships present draught, wave amplitude and squat, preview of the own and neighboring ships planned track (through AIS transponders), display of an extended network of fairways, mimicking the road infrastructure we are familiar with from land transportation. This has earlier been presented at the workshop IST-036/RWS-005 Massive Military Data Fusion and Visualisation in Halden, Norway, 2002. [2] [3]

This system is targeting vessels navigating in high speeds where the cognitive workload is high and decision times short. Accidents involving high speed ferries and military combat boats in Sweden show a need for more integrated and intuitive navigational aids. See figure 2.



**Figure 2: Combat Boat on the Rocks in the Swedish Archipelago 2003.
(Photo: Goteborgs Posten Apr. 26th, 2003.)**

Human cognitive shortcomings are evident not only when navigating in high speeds with limited decision times, but they may also become an issue with slow ships of great mass. Let us take a brief look at the Exxon Valdez accident in 1989.

3. THE WRECK OF EXXON VALDEZ

The following overview is from the Alaska Oil Spill Commission's final report of the Exxon Valdez accident. [4] The numbers in bold in the text refer to the characters in red on map in figure 3.

In the evening of March 23rd 1989 the 210,000 ton tanker Exxon Valdez left the Alyeska Marine Terminal loaded with 53 million gallons of crude oil for Long Beach, California. On her way out through the Valdez

Narrows she was attended by a marine pilot and a tugboat but once in the Prince William Sound she was on her own and began increase the speed. On the bridge was Captain Joe Hazelwood, third mate Gregory Cousins, helmsman Robert Kagan and the lookout Maureen Jones. At 23.24 hours (1) the pilot was dropped off at the entrance to the Traffic separation Scheme (TSS) and at 23.25 Hazelwood radioed to the Valdez Vessel Traffic Center that he had detected ice from the nearby Columbia Glacier drifting in the sound and that he intended to divert from the outbound lane of the TSS and take a more easterly course through the inbound lane “if there is no conflicting traffic”. The traffic center indicated concurrence; there was no reported traffic in the inbound lane. This was evidently a routine maneuver; two outgoing tankers had done the same deviation from the TSS the same day for the same reason. It would save some time in reaching the open sea, instead of having to push her way trough the ice at low speed Exxon Valdes could continue to ramp up her engine to sea speed and at the same time cut a corner for a faster exit.

At 23.30 (2) Hazelwood informed the traffic center that he was changing course to 200 degrees. At 23.39 (3) Cousins plotted a fix in the separation zoon in the middle of the TSS and Hazelwood ordered another change of course, now to 180 degrees, due south. According to Kagan, Hazelwood also ordered the ship to be placed on autopilot. This second turn was not reported to the traffic center. For a total of 19 to 20 minutes the ship now sailed diagonally trough the eastern, inbound lane of the TSS and crossed its eastern border with approximately 12 knots at 23.47 (4) At approximately 23.53. Hazelwood left the bridge after having told Cousins to change course when abeam Busby Light (some 2 minutes ahead).

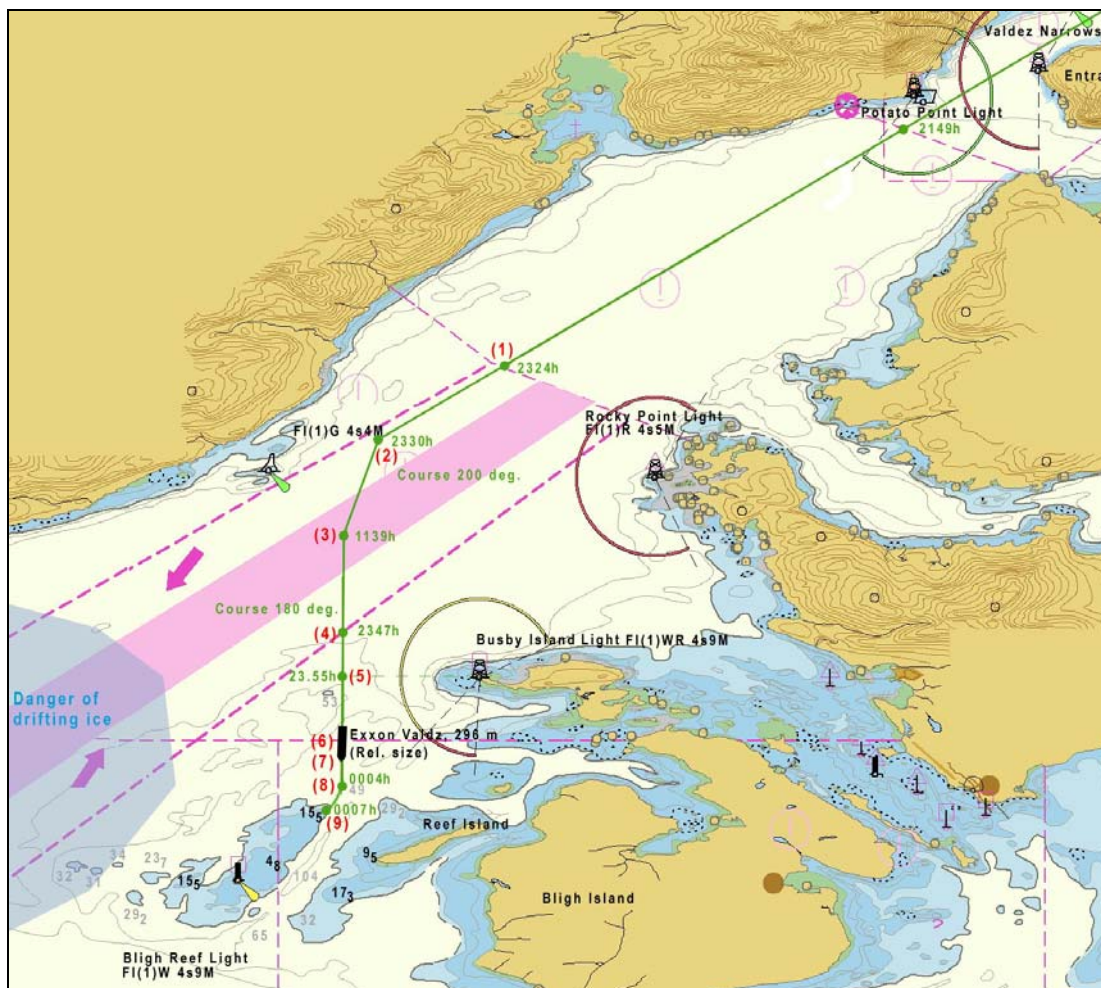


Figure 3: The Route and Times of the Exxon Valdez the Night of March 23rd 1989 in green. The numbers in red correspond to numbers in the text. NOAA ENC US5AK11, 24 and 25M over Prince William Sound, Alaska.

At 23.55 (5) Cousins plots a fix abeam Busby Island but he does not order a turn. For another 5 minutes he continues to take Exxon Valdez on her southerly course. At midnight (6) the lookout reports Blight Reef light buoy broad off starboard bow. Cousins now orders 10 degrees right rudder. Two minutes later, at 00.02 (7) Cousins orders 20 degrees right rudder and at 00.04 (8) hard (35 degrees) right rudder. At 00.07 (9) Exxon Valdez strikes Blight Reef at a speed of approximately 12 knots ripping open 8 of 11 cargo compartments. See figure 4.

The National Transportation Safety Board investigated the accident and determined that the probable causes of the grounding were:

- 1) The failure of the third mate to properly maneuver the vessel, possibly due to fatigue and excessive workload.
- 2) The failure of the master to provide a proper navigation watch, possibly due to impairment from alcohol.
- 3) The failure of Exxon Shipping Company to supervise the master and provide a rested and sufficient crew for the Exxon Valdez.
- 4) The failure of the U.S. Coast Guard to provide an effective vessel traffic system.
- 5) The lack of effective pilot and escort services. [5]



Figure 4: Exxon Valdez Grounded on Blight Reef in March 1989 Causing the Spill of 11 Million Gallons of Crude Oil into the Prince William Sound and the Alaskan Gulf.

As far as the first point goes it is evident that Cousins was too late in initiating rudder and when doing so, he gave too little rudder. In a rare interview with the captain Joe Hazelwood in the *Outside Magazine* in October 1997, Hazelwood is conning a somewhat larger tanker going the exact same rout in a simulator. When abeam Busby light he orders: "Give me right 20." In the simulator the ship nicely turns and passes the reef with a two mile margin. "That's all you'd have to do. That's all anybody would have had to do," Hazelwood is quoted saying. [6]

It is clear that this accident, like many other accidents is part of a big system where rules and regulations, often at high administrative level, contribute to a situation where an accident is only a question of time. But in the specific case, like in the Exxon Valdez accident, there is often a small human error that is the direct cause. Why did the, possibly overtired, third mate Cousins wait for 6 minutes to order the turn?

The hearings give no clear answer. There was no doubt about the ships position. Was his mental picture of the position and extent of the reef distorted? Or did he misjudge the turning capabilities of the tanker?

4. PREDICTING THE FUTURE

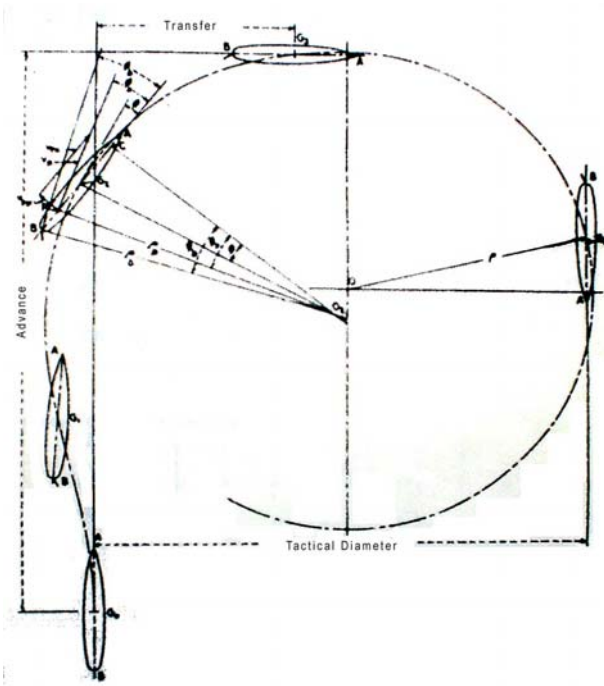
If you know where you are, know where you want to go and have a system that can aid you in finding a safe way with enough water under your keel, there is still one parameter that can put you in trouble: the maneuverability of your ship. Light ships with big machine power and maybe also twin screws and bow thrusters – as is the case with many high speed vessels – seldom has any problems with maneuverability. The case is entirely different with huge ships of great mass.

The biggest ships sailing on the high seas today are of a size of more than 500,000 tons and over 400 meters in length. The forces acting on such a system in motion are very complex, both because of its high inertia and because of hydrodynamic properties and also external forces due to winds, currents, sea states and water depths. I will not go into detail about this because this paper is about visualization. However this is an area well researched by maritime research institutes like for example SSPA Sweden AB. [7]

It is well known that humans in manual control, tracking sluggish second-order systems run into problems. Like steering a fully loaded super tanker where the operator's perceptual mechanisms are called on to perform predictive functions for which the human cognitive system is relatively ill equipped. The reason for this is the lag in the system. It is first after a time delay the ship will answer to a rudder command, which therefore has to be given in advance of the point where the turn is to commence. Once in turning the system will accelerate if the rudder angle is kept. Returning the rudder to a midship position will not for several minutes stop the ship from turning because of its inertia. Instead counter rudder has to be given to stop the turn. Operator control has to act on future, predicted position, velocity and acceleration. This calls for experience. For an extensive overview of manual control of different-order systems see Wickens and Hollands. [8] and for motion on ships in turning Stenhag. [9]

But the future position of a system in motion can be predicted with a reasonable degree of reliability, at least for some minutes into the future if the system has a mass large enough so that control and outside forces are relatively small. A large supertanker is such a system. A device predicting the future position of such a system in motion is called a *predictor*.

Predictors used for maneuvering of ships in restricted waters are very useful for increasing the safety of ships operations. Predicting a ships future position by extrapolation of known parameters like speed and course has been done for a long time. A summary of very early investigations can be found in Kelly [10]. In the simplest version of a predictor, the so-called *speed vector predictor* based on dead reckoning, the ship's position is calculated based on its current position, course and speed, assuming course and speed to be constant. In a slightly improved dead reckoning predictor the turning rate, assumed to be constant, is added to the calculation. In more advanced hydrodynamic predictors information about rudder/propeller/water-jet/thruster settings as well as wind speed and direction is used to improve performance. In the future predictors are expected to be able to use waves and currents as well as waterways and harbor characteristics. [11] In the type of predictors described above mathematical models are derived from the individual data collected at the tests that all new ships undergo. For examples of this type of data see figure 5.



Results from turning tests. Turbine tanker fully loaded, 210,000 tons dw. Starboard turn, rudder angle 34 degrees, from full speed.

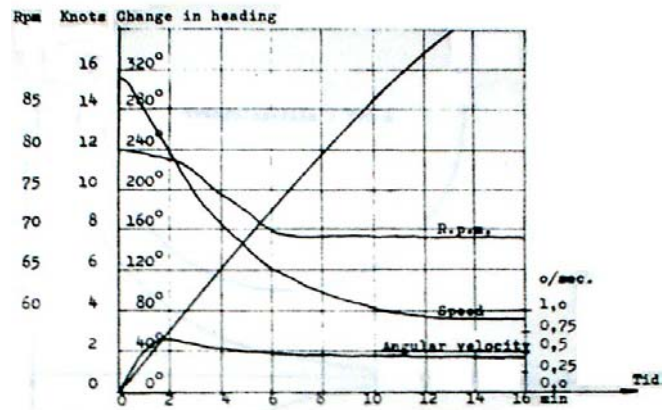


Figure 5: An Example of Turning Data, Collected during Tests Performed with New Ships are Delivered. Left is the turning graph of a ship going into a turn with hard starboard rudder. Note that the ship is moving in the opposite direction when the rudder is turned over, until about three boat lengths when she crosses her own track. Three interesting parameters are Advance, Transfer and Tactical Diameter. Advance and tactical diameter for a fully loaded tanker of 210,000 tons DW (about the size of Exxon Valdez) from full speed (15.5 knots) is 1190 and 1075 meters. To the right is other turning data from the turn of this same ship. [9]

Another parameter that needs to be visualized is the way predicted turning paths is influenced by water depth. In figure 6 we can see three different test turns with the 278,000 tons DW tanker Esso Osaka in different water depths. This has to do with fluid dynamics that are changed when entering shallower waters. The decreased space under the keel changes the escape route for the water particles forced away by the moving hull.

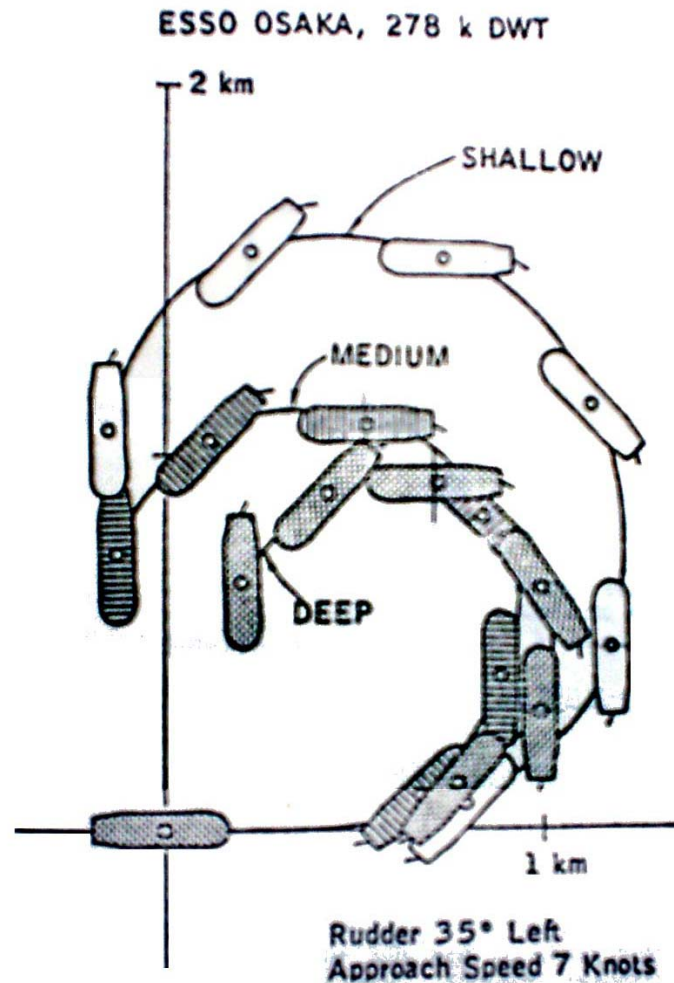


Figure 6: Turning Circles for the Tanker Esso Osaka on 278,000 tons DW. Note that the tactical diameter of a turn is about 70 % larger on shallow water than on deep water. [12]

Further, interesting aspects of turns is that due to the effect of the propeller, the tactical diameter of port and starboard turns is that on a normal ship with a clock wise turning propeller, the tactical diameter of port turns are about 10% smaller. The speed of the ship has surprisingly enough very little influence of the advance and transfer of the turn.

The way of predicting a ships future position can be used in an extended way by predicting consecutive positions into the future for maximum rudder angles both starboard and port. By displaying the results of these calculations in real-time in the chart system, by for example coloring the areas which are out of reach for the ship a trumpet formed visualization of the available decision space is created in front of the ship. See figure 7.

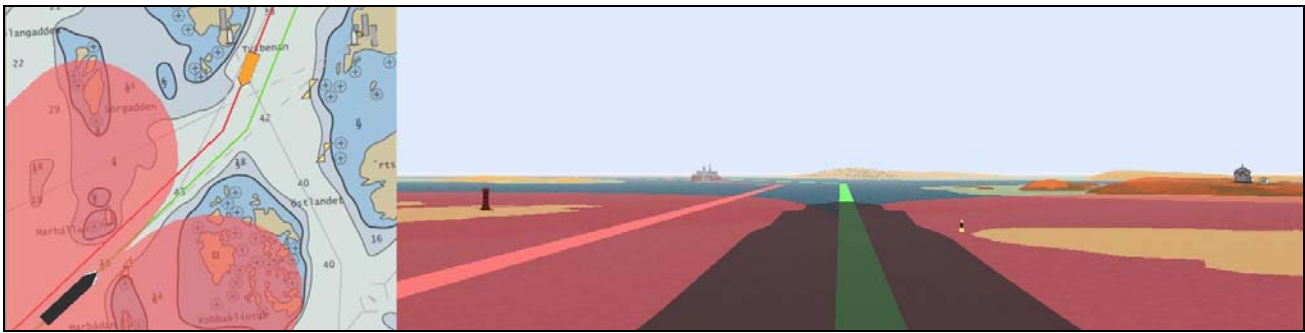


Figure 7: Visualizing the Decision Space of a Ship's Maneuverability in a Real-Time 3-D Nautical Chart. The red area on both sides of the ship is area out of bounds; the trumpet form in front of the ship predicts the borders of maximum turning angle.

In the same manner the stop distance, which changes dynamically with changing speed, can be visualized.

While many features in the suggested decision support system is believed to relieve cognitive workload most effectively during high speeds, it is probable that visualizing the decision space for ship maneuvering shows maximum efficiency for slow moving, heavy ships with limited maneuverability.

The focus of this work is on the information design and human factors issues and not on the underlying hydrodynamic and mathematical models necessary.

5. THE COMMON OPERATING PICTURE

Visualization of the decision space of a ship's maneuverability is of course mostly of interest for the officers on the bridge of the individual ship, but there are civilian situations where shipping authorities could benefit from knowledge of the maneuverability of individual ships. Since 1981 the International Association of Lighthouse Authorities (IALA) and the International Maritime Organization (IMO) has been drawing up rules for a Vessel Traffic System (VTS). VTS centers exist today on many places around the world. They function similar to an air traffic control, but do not have the same directive powers. The Alaskan Oil Spill Commission criticized the Valdez VTS for being too lenient in executing control of the traffic flow in the Prince William Sound at the time of the Exxon Valdez accident. I think that in the future VTS will have more directive powers. Already German VTS centers have a possibility to issue "obligatory order by shipping police direction which must be followed. Refusals and offences can be recorded and prosecuted" [13] I think that to obtain a correct situation awareness, a VTS officer in a control room on shore then can benefit from the ability to virtually "step onto the bridge" of individual ships involved in a developing situation.

Another situation where the proposed system would be useful is in distance piloting of unmanned marine vessels.

6. CONCLUSIONS

As technological development pushes on towards more efficient and faster shipping with smaller crews and more automated bridges workload of the single officer of the watch will change. Many traditional and manual tasks will disappear and will be replaced by surveillance tasks and decision-making. It is important that aids for these tasks are designed from a human factors perspective. By computing maximum turning angles of the ship a few minutes into the future the available decision space of the ships maneuverability can be visualized and cognitive workload can be relieved from the officer of the watch. The visualization

should be presented both in the traditional exocentric view (electronic chart) and in the more intuitive egocentric chart. See figure 7.

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