Managing Abnormal Situations Caused by a Failure in the Automatic Navigation and Steering System

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ABSTRACT

The extensive use of computer technology onboard ships has influenced navigation work. The introduction of automation has been motivated by promises of better safety and increased efficiency. The new technology contains potential safety risks and creates new challenges. Recent accidents have shown that the user s ability to manage abnormal situations is critical for safety. The management of abnormal situations should receive special attention in the design of new systems and in the training of deck officers. In the case of a failure in the steering system, the user must activate the back-up steering mode. This should be done as early as possible, since the time margin for preventing an accident can be very short. Maintaining situation awareness by monitoring the system is crucial. The proposed use of audible feedback for enhancing the monitoring of critical signals is presented. Type specific navigation simulators for abnormal situation training are used by some shipping companies. Since practically every ship is unique, more extensive use of type specific navigation simulators is problematic. The use of ordinary navigation simulators and the need for systematic knowledge assessment is discussed.

1. Introduction

On the bridge of a modern ship, electro-mechanical, manually operated navigation and steering instruments have been replaced by an integrated navigation system. The system consists of computer-based devices communicating with each other through digital interfaces. Many of the tasks that were earlier performed manually by the officer of the watch have been automated. The role of the user in passage execution is to supervise the navigation system, monitor the feedback information on the displays and give orders to the system.

However, the work of the officer of the watch has not become easier. Automation sets new demands on the user and has created new possibilities for making mistakes. The user has to be master of the automation system, knowing what it is doing, why it is doing it, and what it will do in the future. The user is responsible. He must be ready to take the decision and take over the controls whenever the system does not perform as expected.

Faults in a critical component in a navigation and steering system have resulted in accidents (NTSB, 1997), (OTK, 1995, 1998 and 2000). The safety of the navigation and steering systems on ships is of particular interest in Finland, since the south-west coast of Finland is surrounded by an extensive archipelago area. The fairways are narrow compared to the size of the vessels sailing in this area. When the distance to the nearest island is only a hundred meters, the time to the point-of-no-return after a critical failure can be only a few seconds. A gyro compass failure caused the grounding of the ro-ro passenger ship *M/S Finnfellow* near the Finnish coast in April 2000. The grounding took place only 85 seconds after the compass failure. Even though the deck officers noticed that the ship was turning abnormally 30 seconds after the failure, it was too late to avoid the grounding (OTK, 2000).

The user must be able to cope with abnormal situations, such as a missing or erroneous function due to a component failure or software error. The user should also be aware of how the system behaves under extreme environmental conditions. The lack of this knowledge and these skills is a safety risk. Ways to enhance the monitoring of the automatic steering system, training for managing abnormal situations, and assessing the users' knowledge are discussed in the following chapters.

2. The user's role

Reason (1990) states: "The main reasons why humans are retained in systems that are primarily controlled by intelligent computers is to handle 'non-design' emergencies. In short, operators are there because system designers cannot foresee all possible scenarios of failure and hence are not able to provide automatic safety devices for every contingency". The user is not the only human element involved in the safety of a navigation and steering system and in managing failure situations. The human factor is present throughout the life-time of the system: in the design phase, in the assembly, testing and commissioning phases, in the maintenance phase, in the user training phase and finally in the actual operating phase.

The primary task of the officer of the watch is to navigate the ship safely along the planned track by using his/her knowledge, experience and the technical aids available. In relation to the bridge equipment, the officer of the watch has the role of supervisor of the automation system. The user has to perform the monitoring task, when the ship is sailing in the automatic steering mode. The present design principles of such systems give the user a decisive role in a failure situation. In the event of a failure in the steering system, the user should manually activate a back-up steering mode (Ahvenj rvi, 2000). As stated above, the switch-over should be performed as early as possible, since the available time margin to prevent an accident can sometimes be very short.

Maintaining situation awareness by monitoring the operation of the equipment is crucial. This is a demanding task, since users cannot maintain effective vigilance for more than rather short operating periods (Donald, 2001). In order to aid the user in detecting abnormalities, the system contains self-diagnostics and automatic alarm functions. Unfortunately, the self-diagnostics in the integrated navigation system are only able to give an alarm for faults and failures that they can recognize, i.e. for known failure modes. All the intelligence of the self-diagnostics has been coded into the software. A failure mode that was not anticipated by the software engineer will not be recognized by the self-diagnostics - and there will be no direct alarm for it. A missing alarm is a typical cause of a delayed or wrong operator action. Is this an operating error or a design fault? Several accidents have proved the statement that many operating errors are just the delayed consequences of design errors (Reason, 1990).

In consequence, the poor user must stay alert and use his intelligence and experience to compensate for the missing or incomplete parts of the fault diagnostics. Leveson (1995) addresses the monitoring problem by saying: "Unfortunately there is usually no way for a human to check in real time if the computer is operating correctly or not. As a result, humans must monitor the automatic control system at some metalevel, deciding whether the computer's decisions are acceptable." The user should monitor whether the system is operating correctly by persistently reading the feedback signals from the equipment.

2.1 Which data should be monitored?

As there are so many displays and indicators on the bridge, the monitoring task needs to be rationalized in a sensible way. The first thing is to decide which data should be monitored at shorter reading intervals and which at longer intervals.

A simplified structure for the feedback control loop in the automatic steering is shown in figure 1. The navigator s primary tasks on the bridge are to keep the ship on the planned safe track and to avoid collisions with other crafts. For this reason monitoring the status of the process, i.e. the course of the ship and its position relative to the track and to obstacles, must have highest priority.

We can define a dangerous failure of the navigation and steering system to be one that causes an unwanted deviation in the course or position of the ship. From this it could be assumed that monitoring the course and position of the ship is enough to deal with possible dangerous failures. Recent accidents have shown that this does not guarantee safety, if time margins are short (OTK, 1995, 1998 and 2000). Any dangerous failure in the navigation and steering system leads to an abnormal or unwanted performance by the propellers or rudders, since they are used to control the angular and translational movements of the ship. Therefore continuous monitoring of the operation of the rudders and the main propulsion is extremely important when the ship is sailing under automatic steering.

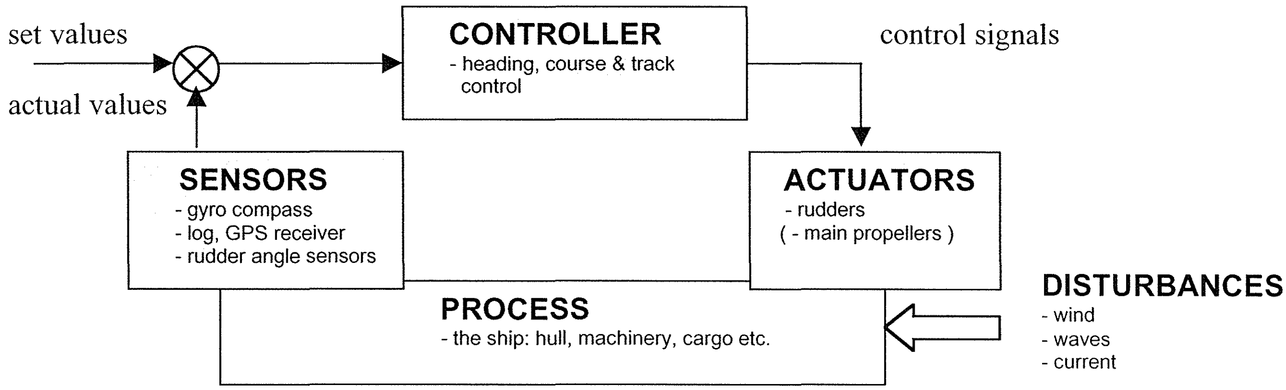

Figure 1. The feedback control loop in the automatic steering system

The movements of a large ship are difficult to monitor - and also difficult to control - because of the great mass of the moving structure. The large mass results in long time constants for translational and rotational movements. A so-called predictor display helps to monitor the ship s movements. The predicted track of the ship for a given time period is displayed assuming that the speed and rate of turn of the ship remain constant. The predictor speeds up the detection of unwanted developments in the position and course by visualizing the derivate of the position and the heading of the ship. The speed and the rate of turn are, on the other hand, integrals of the forces acting on the ship. The forces used for controlling the movements of the ship are the steering force of the rudder(s) and the translational force caused by the main propellers. Changes in the actual rudder angle and the actual propeller RPM and pitch represent an even earlier indication of the future movements of the ship than the predictor. This also confirms the importance of continuously monitoring the propeller and rudder feedback signals.

This can also be seen from some recent cases: In two groundings near the Finnish coast in the 1990's (OTK, 1995 and 1998), a zero propeller pitch due to a technical fault caused the loss of the rudder effect. In both cases, there was an early indication of the abnormal propeller pitch on the bridge, but the users did not look at the indicators. The possibilities of avoiding a grounding would have been dramatically improved if the deck officers had immediately noticed the abnormal propeller pitch. The time between the zero pitch condition and the grounding was over three minutes in the first case (OTK, 1995), and over ten minutes in the second case (OTK, 1998).

2.2 Enhancing the monitoring of critical signals by using audible feedback

The large amount of information makes monitoring a very difficult task. A single conning display can contain over 20 values related to navigation and steering. Apart from this data, the user has the radar display, the chart display, the wind sensor display, the echo sounder display, the communication equipment and many status lamps, meters and indicators related to other systems on the ship in front of him/her. And above all, the user must make direct visual observations about the situation through the windows. It is no surprise that in some accidents the user did not notice quickly enough a critical change in a value on a display or indicator (OTK, 1995), (NTSB, 1997) and (OTK, 1998).

When the bridge is located at the front, no sound from the engines, main propellers or rudders can be heard on the bridge. Information about the operation of this equipment is available only in visual form. Monitoring must be done by continuously scanning the displays and meters. The operator should read the values at short intervals in order to keep the necessary time margin for action if something goes wrong. Obviously these values are not always monitored actively enough. This is quite understandable. Continuous visual monitoring is difficult because information can be received only if it is close to the primary attention focus of the user (Rauterberg and Cachin, 1993). The operator has to deliberately look at the readings on the display or indicator. Again, for most of the time nothing abnormal can be seen on the displays, which is a strong demotivating factor.

Our hypothesis is that monitoring safety-critical signals on the bridge could be improved by using audible feedback. i.e. by producing a continuous background sound for the operational status of the rudders and the main propellers. Critical faults in the navigation and steering system would then be detected earlier, which would improve the safety of automatic steering.

The idea of audible monitoring can be demonstrated by a simple example: we have all learned to recognize the sound of our own car when the motor is started or when the gear is changed. We are immediately alarmed if the sound is different. Similarly, bridge officers would learn how the propellers and the rudders sound at different points of the route under normal weather conditions. The detection of abnormalities would then become automatic.

The potential of multimodal interfaces has been studied by many researchers. A well-known experiment using auditory cues in monitoring a complex system is the ARKola bottling plant simulation reported by Gaver *et al.* (1991). The effect of sound feedback on the work of a plant operator has also been studied by Rauterberg *et al.* (1994). Rauterberg states that the most important advantage of sound feedback is its attention-demanding ; it breaks in on the attention of the user. The detection of changes in the background sound happens automatically, without the need to pay special attention to it. The sense of hearing is an all-round sense. This is a very important difference compared to visual perception, which is a directional sense.

Questions to be examined in further research on the subject are listed in the table below.

Table 1. Main topics for further research on the use of audible feedback in monitoring.

The topic to be examined	Explanation
What requirements are set for the additional feedback sound by the existing sounds on the bridge of a typical passenger ferry?	Real sounds onboard a passenger ferry in different weather conditions will be measured. An identical background sound will be created for the navigation simulator. The frequencies, tone and volume of the audible feedback should be selected so that the sound can be heard under all conditions and, on the other hand, so that the feedback sound does not obscure speech or any other important sound on the bridge.
What kind of sounds would be acceptable to users?	Adding the background feedback sound must be accomplished in such a way that it does not disturb or irritate the users or cause additional mental stress. In the experiment of Gaver, a natural sampled engine sound was used (Gaver *et al.*, 1991) whereas Conversy (Conversy, 1998) used a real-time filtering technique to create wave- and wind-like sounds.
What kind of changes in the background sound attract the user's attention?	The user should immediately notice any abnormality in the feedback sound. Many parameters can be varied: the pitch, volume, timbre, tone, direction or repetition frequency of the sampled sound patterns etc. The effect of different ways of varying the sound must be examined.
Does sound feedback improve operator performance in fault situations?	Introducing audible feedback should speed up the detection of critical faults in the automatic navigation and steering system. A navigation simulator will be used to measure the efficiency of the sound feedback. The result for fault detection with additional sound feedback will be compared with the results without sound feedback.
What is the effect of learning?	The users should learn how the healthy system sounds. Learning the healthy feedback sound is the key to detecting abnormalities. This shall be studied using simulator exercises.
Does audible feedback have a similar effect on the performance of all users?	There may be differences between individuals in reacting to the sound feedback. The navigation simulator shall be used to study this matter.

3. Training of users

It may be difficult to see any difference between the performance of an experienced user of an automatic steering system and that of a novice under normal operating conditions. But the difference becomes apparent when an abnormality occurs in the operation of the system or in the conditions where it is being used. A novice might act in the wrong way or take no action at all, whereas the skilled operator would be able to manage the situation without problems. Managing abnormal situations is the most demanding area in operating an automation system and therefore should receive much attention in the training of users.

Properly arranged, continuous user training is an important means for reducing the safety risk in automation systems. It can even reduce the safety risk due to design errors. Operator training should contain not only exercises in using the system under normal operation conditions but also a large, carefully designed set of exercises in managing the system under abnormal situations, for the following reasons:

- An abnormal situation such as a failure situation or extreme operating conditions means a higher safety risk. The risk of an accident is greater and therefore any error made by the user could have more severe consequences than in normal operating conditions.

- Redundancy in existing navigation and steering systems is usually realized in such a way that in the event of a failure the user has an active role in selecting the stand-by device or back-up function. The threshold for activating the manual control mode after a fault could be kept lower by giving training for various situations in a simulator.

- The skills for managing different kinds of abnormal situations cannot be learned or maintained during normal operation onboard.

- There is always the risk that users become over-confident if in their experience the automation system is always very reliable. Demonstrating potential failure cases could provide motivation for users to continuously cross-check and monitor the system properly.

- Training in different failure cases gives the users the chance to correct their mental model about how the system will behave in different conditions.

- Becoming familiar with an abnormal situation reduces the mental stress when a similar situation occurs in reality, which reduces the risk of an operator error.

- Simulating critical situations can give information about the individual's ability to act under stress.

Reason (1990) says: "One of the consequences of automation is that operators become de-skilled in precisely those activities that justify their marginalized existence. When manual takeover is necessary, something has usually gone wrong; this means that operators should be more rather than less skilled in order to cope with these atypical conditions".

3.1 The need for type specific training simulators

It is quite obvious that learning to manage abnormal situations cannot be achieved by reading books or manuals. The more rapid the reaction needed, the more important it is to train in the correct procedures in advance, hands-on. The training also needs to be repeated at reasonable intervals. High-quality simulators have been used for more than twenty years in training nuclear power plant operators and aircraft pilots to handle abnormal situations. A realistic and well tuned type specific simulator is an ideal tool for operator training. In the simulator trainees can make their own, direct observations and obtain their own experience of how the system behaves in abnormal situations. All training cases and scenarios can be repeated as many times as needed. The procedures taught can be directly applied in operating the real system. Trainees can also compare their own mental model with the behavior of the system and make corrections if needed.

The realism of the simulator is crucial. The Human-Machine-Interface of the simulator equipment, the operating logic and the behavior of the process should be as close to reality as possible. Trainees should experience the simulated situation and the behavior of the system as it happens in real life. Otherwise they are not learning the right thing. The reality of the simulation may also have an effect on the motivation and attitude of the trainees. If the simulator equipment or its behavior does not match reality, this may make it impossible to reach the stress level that exists in a distress situation. This would lessen the effectiveness of the training, since mental stress is an essential factor when managing abnormal situations.

However, high-quality simulator facilities do not automatically mean good training results. Training sessions must be carefully planned and the exercises performed in a professional way, taking into consideration the laws of human learning. All training scenarios should be realistic. Documented incidents and accidents are an excellent source of realistic training scenarios.

3.2 The problem of standardization

A type specific simulator, i.e. a simulator that is identical to the actual bridge on a ship, is not common in the training of navigators. The reason is simple: the level of standardization for complete bridge systems is still very low, and so a navigation simulator with a type specific bridge equipment and simulation model would be compatible with very few ships.

There are thousands of different ships in the world and almost every ship type has a unique bridge layout. There have been some brave efforts to create integrated bridge standards, but with poor results.

Since competition, the shipbuilders and the regulating authorities do not give sufficient support for the strict standardization of integrated bridges, the leadership in the work of standardization should be taken by the shipowners. Some of the most important benefits from using a standard bridge concept on a whole fleet are:

- *Training costs*: the costs of high quality training are much lower when the same written material, CBT programs and type specific simulation equipment can be used for training all deck officers

- C*osts and quality of maintenance*: spare part costs, overall maintenance of equipment, training of electricians etc. can be optimized when there is a company bridge standard.

- S*afety*: the special technical, operational and training expertise derived from a company bridge concept will promote safety. The opportunity of using high-quality type specific simulator equipment for crisis management — not only for training operators but also for testing purposes - is also essential. Another important factor is the possibility of moving deck officers from one ship to another without the risk of having users with too little knowledge of the system.

The development of computer electronics has been very rapid during the past twenty years, which means short product lifetimes. From the system manufacturer's point of view, the product development cycle should be as short as possible and a new product generation should be introduced ahead of competitors. But if manufacturers are introducing new product generations every third year, it becomes practically impossible for a shipowner to create a company bridge standard. Very few shipowners can afford to replace the integrated bridge of the whole fleet every five or seven years. Compared with the typical lifetime of a ship, even ten years is short for the lifetime of equipment.

3.3 The use of ordinary navigation simulators

It is difficult to see any other method that would be superior to using a type specific navigation simulator in training deck officers to manage abnormal situations. However, without major developments in the standardization of bridge concepts, few new type specific navigation training simulators are likely to be introduced. Most deck officers will have to continue their work without proper simulator training in managing abnormal situations.

One possible solution to the lack of type-specific training opportunities would be to make special use of existing simulator facilities to demonstrate real incidents and accidents, examine potential failure modes in navigation and steering equipment, and train in generic crisis management procedures, that would apply to a particular ship with small modifications.

The behavior of a human being when performing a control task can be described with the well-known three-level model proposed by Jens Rasmussen (1987): the skill-based, rule-based and knowledge-based levels. At the skill-based level, performance is governed by stored patterns of preprogrammed instructions. At the rule-based level, solutions are governed by stored rules. At the knowledge-based level, actions are planned using conscious analytical processes and stored knowledge.

A type specific simulator is obviously needed to provide efficient training at the skill-based level. But a well designed, realistic general-purpose full-mission navigation simulator - which would have the necessary features for demonstrating various equipment failure modes on different ship types - could be used to train for operations at the rule-based and knowledge-based levels. This kind of training would teach the right attitude and raise the level of awareness of the potential risks in using automated systems. It would also emphasize the importance of continuous monitoring and cross-checking during the use of an automated system and the user s role in managing abnormal situations.

The use of general simulators in crisis management training as described above should of course also be applied in the training of deck officer students at maritime education and training institutes.

3.4 Knowledge assessment

An assessment of the users' competence should be included in all training. No training course should be completed without an evaluation of its effects. This information is necessary for the ongoing development of the training. Ineffective training practices and scenarios can then be eliminated and better ones developed.

A test is also a good motivator. This fact is well known by everyone working in the field of education. When trainees know that they have to pass a test, they are better motivated to learn. Competence assessment of deck officers is also a requirement of the STCW 95 and should be carried out on a regular basis. The methods for demonstrating competence defined by STCW 95 include the use of simulators. The aviation industry has long experience of using simulator tests for this purpose.

The skill-based and rule-based behavior of the operator could be tested by running suitable tests on a simulator. For testing the mental models and knowledge of the operators, a traditional written exam, in the form of open questions or multiple-choice questions, would be a good choice. A computer-based tool, based on a large set of multiple-choice questions, could be used for this purpose.

4. Conclusion

The user s readiness to successfully manage abnormal situations is crucial for the safety of automatic navigation and steering systems. Continuous monitoring of critical feedback data is important, since the built-in self-diagnostics of the integrated systems do not necessarily cover all failure modes. On restricted waters, the operation of the rudders and the propellers should be actively monitored when the ship is sailing under the control of an automatic steering system. Monitoring could be enhanced by using audible feedback.

The management of abnormal situations should also have a high priority in operator training. The operator is the critical resource that should be able to find the way out of a hazardous situation after a failure in the automation system. The need for simulator training for specific navigation systems is obvious. Training in the exact procedures for handling different kinds of failure situations can only be effective when using a simulator that is a copy of the real system. The problem in establishing type specific training simulators is the lack of bridge standards. Almost every new ship type has its own unique bridge layout. Companies would gain many other benefits from building company standard bridge concepts.

Because of the obvious problems in establishing type specific navigation simulators, the potential of general-purpose simulators in crisis management training should be utilized as much as possible. The performance of the operator can be described with a three-level model consisting of the skill-based, rule-based and knowledge-based levels. A general-purpose full-mission simulator could be used to train users in managing abnormal situations at the rule-based and knowledge-based levels.

Training activities should be supported by a systematic assessment of the skills and knowledge of the operators. A simulator trial is a convenient method for testing skill-based and rule-based level performance. For testing knowledge-level performance, a testing method based on an extensive multimedia question database could be used.

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