Analysing Context-dependent Deviations in Interacting with Safety-critical Systems

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Abstract: Mobile technology is penetrating many areas of human life. This implies that the context of use can vary in many respects. We present a method that aims to support designers in managing the complex design space when considering applications with varying contexts and help them to identify solutions that support users in performing their activities while preserving usability and safety. The method is a novel combination of an analysis of both potential deviations in task performance and most suitable information representations based on distributed cognition. The originality of the contribution is in providing a conceptual tool for better understanding the impact of context of use on user interaction in safety-critical domains. In order to present our approach we provide an example in which the implications of introducing new support through mobile devices in a safety-critical system are identified and analysed in terms of potential hazards.

Keywords: user interfaces, safety-critical systems, context of use, mobile devices

Introduction

In recent years there has been an increasing availability and use of a wide range of interactive devices, in particular mobile devices. This type of technology is penetrating many areas of human life. In interactive safety critical systems the introduction of new technology is often slow because people need to carefully understand their implications in terms of potential hazards. Only recently these issues have started to be addressed also in safety critical applications, such as air traffic control [1], control rooms [2] [3] , fire fighting [4].

In this paper we present a novel method that aims to help designers in managing the complex design space when they address applications that should be accessed through varying context of use and the goal is to improve usability while preserving safety.

Our method is based on integrating a systematic analysis of deviations with a Distributed Cognition approach [5] [6] [7], so as to put more explicit consideration of the distributed cognitive resources supporting task accomplishment. The underlying idea is that a criticality or breakdown in task performance is the consequence of an *inadequate access to information* important for the cognitive processes involved in task accomplishment.

Deviations analysis includes systematic analysis of potential effects in case of deviations from the task plan. Such deviations include not only ‘human errors’ according to Reason’s terminology (skill-based, rule-based and knowledge-based errors, see [8] [9]), but also consideration of possible incorrect behaviour of the interactive system. In order to help with such analysis, a number of deviation types (indicated by *guidewords*, such as ‘none’, ‘other than’, ‘ill-timed’) have been identified. The approach is supported by task models, which are suitable to providing an overall view of the possible activities but may not be able to capture all the possible contextual aspects. This information can be provided through the support of Distributed Cognition analysis, which focuses on how knowledge is distributed across individuals, tools and artefacts in the considered context/environment. One basic point is that any breakdown in task performance is the consequence of inadequate access to the distributed representation of information resources supporting task performance. One limitation of this approach is the difficulty of translating its results into specific design criteria. Integration with the analysis of tasks and their performance can create the basis for addressing this issue. In this process the idea is that the final representations provided should be suitable for the activities to support but can radically differ depending on the interaction resources available on the device at hand. In the paper we describe and discuss the proposed method and show its application in a real safety-critical context, an Air Traffic Control Centre, for which we analyse the possible use of mobile interactive devices for supporting a specific role and some activities.

The Method

The basic idea of this paper is to evaluate how much the context could affect the possible hazards inherent in a particular design in order to identify possible areas for improvement in order to prevent human error. Indeed, when a safety-critical application is considered, any analysis should perform risk analysis on the current design, namely understanding what errors can occur and their potential effects in order to evaluate whether the current design is acceptable or new solutions should be provided to manage hazardous situations that might occur. As soon as such areas of improvements have been identified, the next step is to identify and specify a new arrangement/distribution of activities, roles, artefacts and devices in order to compensate for the identified shortcomings. Such specification should describe how the activities are supposed to be carried out in the new system, also specifying how they evolve over time, the context in which they are supposed to be performed, the roles that are expected to be covered, and the artefacts and/or devices available in the new setting.

In analysing potential improvements it is also possible to consider the impact of new technology, such as mobile devices.

Analysis of Deviations

In this section we provide a more detailed description of the method proposed. One starting point for this research was deviation analysis [10]. It has been extended in order to identify and consider several aspects: the context of use in which tasks are supposed to be performed (comprising the user/role, the device(s) used for interaction, and the surrounding environment), the distribution of representations in the analysed context of use, and the deviations that might occur. Given a context of use the following phases are performed:

- Analysis of tasks and related properties
- Analysis of the representations/resources needed to perform the tasks in the considered context
- Consideration of a specific type of deviation occurring while performing a task in the supposed context
- Evaluating the current configuration of representations supporting tasks
- Recommendations for an improved design through:
    - Alternative distributions of resources
    - Alternative representations of information

The results of such analysis may be stored in tables with the following information:

- *Task*: the activity currently analysed, together with some properties relevant to our analysis;
- *Context (user, device, environment)*
- *Representation distribution*: the resources supporting task performance and their distribution in the considered context of use;
- *Guideword/Explanation*: the type of interaction failure considered and how it has been interpreted for that task and the given deviation;
- *Causes*: the potential causes for the interaction failure considered and which configuration of resources might have generated the problem;
- *Consequences/Protections*: the possible effects of the interaction failure in the system, together with the possible protections (if any) already existing in the considered system;
- *Recommendation*: suggestions for solutions able to cope with the potential hazardous situation, e.g.: an alternative (if any) distribution of resources.

The deviations analysis can be applied to any application domain, even if detailed consideration of causes, consequences and recommendations is particularly meaningful in the case of safety critical systems. By way of example, we can consider a simple activity such as printing and a deviation type such as None. This means that the printing has no effect and we have to understand why this happens. This could be for several reasons: no input information (the user did not correctly select the file to print) or the activity is not performed (the printer is broken) or the activity is performed but does not generate the result (the printer is out of paper).

If potential safety-critical issues have been identified, then our analysis aims at identifying better representations (or distributions of them) that could be more suitable for carrying out the considered tasks and prevent occurrences which can have safety-critical effects. The evaluation has to consider whether a different allocation of resources may be envisaged, which implies different representations of information and could involve considering different devices, that may result in a significant improvement for the overall system's safety and usability.

The goal of the analysis of the information representations is to understand whether they provide adequate support to the achievement of the task goal or alternative solutions should be pursued instead. To this end, a number of important attributes have been identified:

Externalisation: the extent to which the representation is explicitly provided in the real world or is based on implicit, internal representations.

Accessibility: whether it can be problematic for the user to access the information because it is difficult to see or to hear or for any other reason.

Access modality: the type of access to a representation that a user has. Different types of access (sequential/concurrent) could be exploited for externally available representations.

Mobility: whether access to the information requires the user to move first or the user can access information while moving.

Sharing: refers to the extent of the perception of a representation: i) Local to individuals; ii) Shared (e.g. by the members of a team); iii) Globally available to all. This property might be connected with the type of supporting platform (for example if controllers annotate a strip on their PDAs, this information will be available locally only to them).

Persistence: whether transient or permanent access to information is allowed.

Flexibility of modifying the representation, ability to flexibly update and modify the representation, for example allowing a person to annotate an external representation (i.e. strips).

Operations and actions supported such as:

Comparability: with other objects / representations available in the user's context;

Combinability: allowing users to combine information from different sources;

Ease of production: allowing reconfiguring and multiple views of information;

The analysis of deviations is based on examining a representation of the system's design to ensure that necessary features are incorporated with the intent of identifying states that could lead to undesirable outcomes (hazards). The process of using guidewords to suggest deviations, and then searching for hazardous effects, possible causes and related remedies, has the objective of judging if the current design is able to prevent hazardous effects and, if not, provide possible recommendations to improve the design. Indeed, an evaluation of the risk associated with such hazards is needed in order to estimate if the currently existing protections are enough to prevent dangerous consequences, or further countermeasures are necessary in order to minimise such risks.

This analysis is based on the HAZOP process, which historically originated from the chemical industry, and therefore is greatly concerned with components and flows between them, trying to find causes for e.g. no flow, too much or too little flow, partial or reverse flow. When we consider interactive software systems, these chemical criteria are directly translated into more generic flows of data occurring during the interaction. Actually, in our method, we investigate not only the effects of omissions or late delivery of data, but also the effects of deviated performance of tasks during interaction, which means evaluating the effects of e.g. not performing the task at all, or neglecting to perform a part of it, or, alternatively, executing an additional, unnecessary activity, and so on. The aim of applying such analysis is to identify the most safety-critical areas of the interactive system, so as to focus efforts on these areas. In this way greater confidence can be placed in the resulting system performing its interactive functions.

However, when we developed this method we soon realised that a hazard is defined with respect to the environment of the system considered, so when applying such analysis it is necessary to consider the context in which the interaction occurs because modifying the operational environment in which a software application is executed may alter the associated hazards. Therefore, safety in using applications must be considered in the context of the overall system in its operating environment, and this is exactly what we are going to perform in the next section where we consider how the different *contexts* might affect the hazards associated with the same task. As in the literature there are a number of different definitions of context, it is important to define what we mean by this term. We mainly refer to context by considering three different dimensions: the users/roles considered, the devices used for the interaction, and the supposed environment in which interactions occur, intended both in the physical sense (the surrounding environment) and in the socio-collaborative one, because when a cooperative work setting is considered, community issues such as team coordination and task division have to be taken into account.

It is worth pointing out that the different dimensions are not completely independent of each other: for instance, when we suppose a certain user/role, generally the expected device(s) used are roughly defined, as well as the environment in which the interaction will occur. In this paper we are going to consider the way in which variations to the context might affect the types of deviations identified. To this end, we consider a case study in the air traffic control domain, in such application we focus on the effects of varying the devices used by ATC controllers by means of comparing and contrasting the current controller environment with an envisioned one in which a mobile device is used by the supervisor, a controller who might plausibly move around the control room.

The Case Study

In order to show an application of the approach described and understand its feasibility, we consider a real application domain, the Air Traffic Control, which traditionally brings a high number of complexity factors (environmental, collaborative, organisational, cognitive,..). However, for sake of brevity, in this paper some assumptions/simplifications will be done about such complexities, also to make the reader more easily understand the main ideas of the approach. We extracted a case study in the working environment of Rome-Ciampino control centre in Italy, where there is a number of en-route and approach working positions in charge of controlling, respectively, cruising flights and airplanes taking off/landing from/to the nearby major Fiumicino airport. In addition, there are other stakeholders (a chief controller, a technician supervisor, a flow controller), together with three or more supervisors having the responsibilities for making decisions about closing/opening sectors (usually in a vertical manner), depending on data about the estimated traffic load and airport capacity.

Air Traffic Management is based on the concept of airspace division into a number of sectors. The number of flights that are planned to cross a specific sector is called traffic demand. The maximum number that may be in a certain sector simultaneously (namely the number of flights that the sector itself is able to handle for each hour) is called traffic capacity and can be calculated using a number of parameters (types of flights, air complexity, etc.). When the controllers in charge of the flow position recognise a situation in which the traffic demand exceeds the sector capacity, they coordinate with the supervisors and chief controller on the actions to be taken (e.g.: some flights might be redirected through a different path with the same length, or a regulation might be triggered). In the current system, controllers use graphs visualised on paper-based documents such as that displayed in Figure 1, to analyse the variation in the traffic demand during (a part of) the day. As it can be seen from the picture, the maximum capacity of the concerned sector is 40 flights (see the threshold line at the value of 40 on the Y axis in Figure 1): as the Y axis shows the number of flights that are supposed to cross the sector, it means that the sector is supposed to manage a maximum number of 40 flights per hour However, during the day, there might be some 'peak hours' in which the expected traffic (traffic demand) might exceed such a limit (sector capacity). Indeed as it is possible to see from Figure 1 (where the X axis represents the time in hours), such 'peak hours' are concentrated within the the time interval 11:00am-15:00pm . Therefore appropriate actions (e.g.: regulations) should be triggered by the controllers, so as to cope with the expected excess traffic demand.

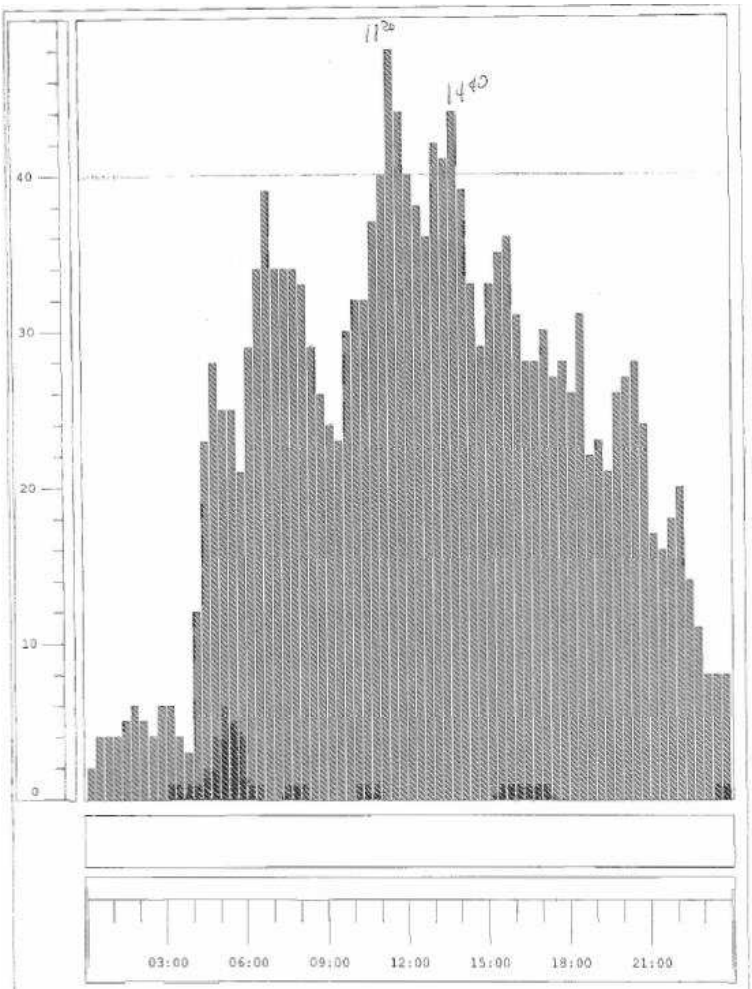

Figure 1: A working tool for the flow controller in the current environment: foreseen traffic displayed with paper bar charts

The centre *manages information about the upcoming traffic* and decides on possibly triggering division of one sector in two sectors or absorption of two or more sectors into one sector, depending on data about the estimated traffic size and the airport capacity, and also personnel resources available on site.

The ATC supervisor can be regarded as the only role without any “dedicated” position within the control room. The need to have continuous access to real time traffic information may imply a high level of mobility in the control room.

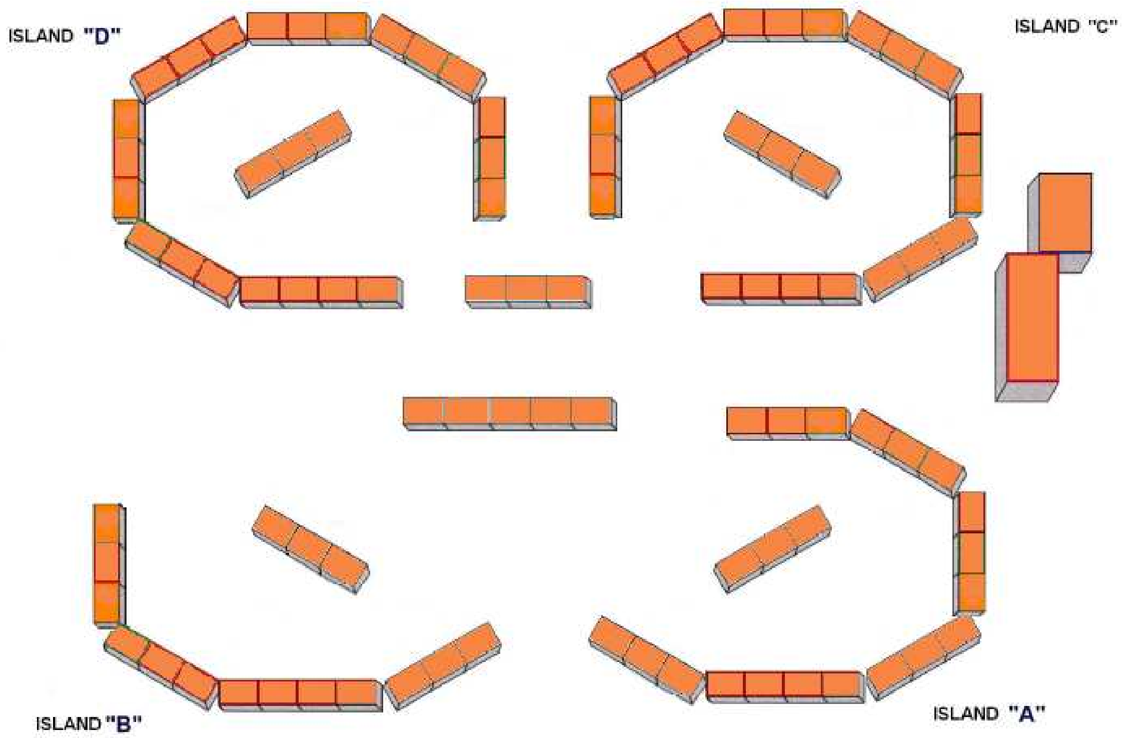

Figure 2: Simplified representation of the control room.

In Figure 2 a simplified representation of the Ciampino new control room is visualised (the area in which the supervisor is expected to be found is roughly the central one). In order to de-combine two air space sectors, the supervisor has to identify overloaded air traffic sectors, and the level of criticality of the upcoming air traffic; at the same time, s/he has to evaluate the on-site workload allocation of the controllers, and also to identify the personnel available to assume control of a new sector. In this scenario the ATC controllers have to decide whether to open a new sector or not by checking the critical threshold of the upcoming air traffic level. In order to perform their activities, they use an integrated set of tools (computer displays, telephones, paper-based documentation). In addition, they need real time access to information about the current and estimated up-coming air traffic levels, as the decision to open a new sector will be further based on the information manipulated by this task and available from several sources distributed in the task space: flight information system, air traffic monitoring system, radar, flight progress strips, meteorological information, etc.

Applying The Method to the Current System

The first option considered basically refers to the current situation of ATC centres described in the previous section. As we previously pointed out, one of the supervisor's main tasks is *deciding about splitting/merging sectors*. To this aim the controllers need to access to various sources of information (computer-based and paper–based information: e.g. meteorological, foreseen flow of traffic, current situation of personnel, …); and need to cooperate and interact with other roles in the room (e.g.: the flow controller). As a consequence of such supervisor's need of mobility and coordination, together with the fact that no "dedicated" position in the control room exists for the supervisor controller, is the fact that they are required to move in the control room in order to collect appropriate information on which to make the decision of opening additional sectors. Such information may be collected by means of tools and data, but also in the shape of coordination/communication with other stakeholders in the room, which may force the controller to remain far from the concerned tools and information for some time.

It is possible to apply the deviation analysis to the case study to identify potential safety-critical issues. If we focus on the context of use we can say that the user is the supervisor, the device(s)/tool(s) used are mainly desktop-based system with multiple displays together with paper-based documents and, in addition, as for the environment, we have the physical environment of the control room in which there are other stakeholders (e.g.: flow controller) with whom the supervisor coordinates.

If the analysis of representations is applied to our case study we can notice that several information objects supporting task performance may be identified: normal and critical threshold of upcoming air traffic level, additional parameters such as estimated numbers of aircraft, together with time intervals, planned trajectories, etc. In particular, such thresholds of upcoming air traffic level are visualised on paper in the form of a bar chart, such as that visualised in Figure 1. In this context, if we consider, for the task supporting merging/splitting sectors, the possibility that the information needed is not available, there are some possible causes that might be identified. For instance, *the information is not visible* and the possible causes are that there are some difficulties in perceiving the relevant information due to some usability issues (the object represented is too small, ambiguous shape, wrong choice of colour, etc.; but also supervisor' s distraction / interruption by other activities, etc.). Another factor that might cause the lack of information is that, for example, the controller is currently far from where the information is being visualised. In other cases, *the representation might not be persistent*, due to rapid change of information values, which does not give the user the necessary time to internalise the perceived information and to integrate it with the other information supporting his decision making. As for possible consequences, if there is no (updated) information available in the task performance space (not visible, not persistent) then various types of task failure can occur: decisions are made on wrong assumptions/hypothesis or on information not up-to-date, delays occur on task performance, ..

As for the possible protections, we mention the fact that time constraints are not highly strict for supervisors: when they are back at the stationary positions, they still should plausibly have the time to make decisions at the right time and act consequently. However, while there are not high safety-critical consequences that may compromise in real time the safety of the system, the opportunity for the controllers to have the information always available and up-to-date even while they are moving in the room arises in order to improve the quality of interaction/communication/coordination with other controllers and the level of continuous monitoring of the system.

Applying The Method to the Envisioned System

As the first step of the analysis has highlighted the need for the controller to have information available while moving round in the control room, then, a new specification of the activities together with a modified distribution of related resources should identified. In the envisioned system, the activities should be carried out so as to allow controllers continuous access to the information needed to perform their activities. The new specification should identify the new context in which the activities are carried out, and the new arrangements of resources/devices.

More specifically, the envisioned system calls for providing the controller with a mobile device to display the critical information. The controller needs to access such information in real time, so it should be always available, and, to this end, the possibility that such information should be visualised on a PDA might be envisaged in the new system. Then, in this case, due to the limited capabilities of the handheld device, only a selected subset of the data normally displayed by the current system tools should be visualised on such devices. In addition, as the user is supposed to be mobile, specific presentation techniques able to cope with the rather noisy environment of the control room should be foreseen and the eventuality that the controller not watch the device constantly be adequately controlled for.

In addition, special attention should be paid on how to render some specific types of representation (such as those used in the ATC case study considered, e.g. bar charts and line charts) in order to understand the best way to render such data on the small screens available on handheld devices such as PDAs.

Analysis of the Resulting Representations in the Example

The application of our approach to the case study can find a more efficient manner of showing data needed to the ATC controller in a PDA-enabled new system, as a consequence of ensuring a greater level of safety in situations such as that highlighted by the deviation-based analysis previously performed, in which the controller might be temporarily unaware (because, e.g. is distant) of some critical information currently visualised on some tools.

In the new, envisaged system, the mobile device enables the controllers to move around the control centre bringing with them the device so as to get a full, continuous awareness of the expected situation.

In the envisioned system the supervisor is equipped with a mobile device(e.g.: a PDA), which is expected to be used when the controller is forced to move around the room so as to allow the controller to have critical information always available to the controller.

Moreover, in the envisioned system the stationary desktop-based tools used by supervisor remain substantially unaltered, while suitable information visualisation techniques able to render critical information should be used on the mobile device, so as to exploit in the best way the limited screen capability of the PDA.

In the new, envisaged system, the mobile device enables the controllers to move around the control centre bringing with them the device so as to get a full, continuous awareness of the expected situation. In addition, thanks to the fisheye view-equipped graphs (see Figure 3) that we have designed for the controllers' PDAs, it is possible for them to more properly focus on the current area of interest, which are the intervals of time when the threshold limit are likely to be overcome. Moreover, there is the possibility for the controller to have additional information on specific time intervals, by tapping-and-holding the pen stylus on some specific bars, so as to have visualised more precise information on the concerned values. For instance, in Figure 3, the controllers have currently focused their interest on the period of time between 12:40 and 13, and a tooltip is displayed in order to more precisely show that the number of flights that are expected for that period of time is 42, which is beyond the supposed capacity of the sector.

Figure 3 - The Fisheye Viewed Bar-Chart with Flight Information for PDA.

In the new system, if we consider the possibility that the representation of interest is not available, there are some possible causes that might be identified.

In the remainder, we will focus only on the situations in which the use of mobile devices are involved, because the conditions in which the stationary platforms are used are supposed not to change. Under this hypothesis, and analysing the same task we considered in the current situation ((de)combination of sectors) one possible cause for no information available to this task is that the controller is moving around the control room and the mobile device is not available because of some external causes (s/he has forgotten the mobile device; the mobile device is broken/out of battery power). Another possible cause is that the mobile device is available but it is actually not used (the controller is not currently watching at the mobile device because e.g. is currently interacting with other controllers, or s/he is overconfident,…). As an alternative case, the mobile device is available and is actually used by the controller, but information is not displayed because of some technical problem (e.g.: network, etc.). The last option about the use of mobile device is the possibility that the mobile device is available and used, suitable information is displayed but some usability issues arise (e.g.: information not readable or ambiguous because of interaction/visualisation problems, or the objects represented on the mobile device are too small, the contrast is not sufficient with the conditions of the place of the control room in which the controller currently is). In addition, if the supervisor is supposed to be currently moving and far from his/her work location, on the one hand the possibility for a supervisor' s distraction / interruption by other activities/members in the room results to be higher, compared to when the controller is at his/her work place. However, on the other hand, this situation (controller 'on the move') does not represent anymore a cause for the controller not being aware of the current situation (as in the first option), because in the new system the controllers are supposed to bring the mobile devices with them. As for possible consequences, if there is no information available in the task performance space (not visible, not persistent) then various types of task failure can occur (e.g. stopping task performance, delay, making wrong decisions etc.).

As possible envisaged protections for the situations in which the mobile device is not available is the fact that the information is still available on the desktop-based system: controllers are aware of the abnormal situation occurring on the mobile device and can act upon by coming back to the stationary system.

If, on the other hand, the problem is in how the information is represented (possible ambiguities, etc.), the solution is in relying on multiple ways of representing the same information (different, redundant representations available on the PDA). As for the recommendations, the use of appropriate alerts able to capture that attention of the controller in the surrounding rather noisy environment should prevent controller from not being aware of any hazardous situation currently in progress, even when they are on the move.

Then, as a result of this analysis, a possible r*ecommendation* might be to rely on multiple levels of redundancy for representing/communicating critical information. In fact, while the mobile context allows for greater flexibility, the supposed environment of use might vary even more, then redundancy may allows the controller to select the most appropriate way for interaction. So, as a result of this analysis, a possible r*ecommendation* might be to rely on multiple ways of representing the same information (e.g., visual and auditory): access to concurrent representation of the same information could be especially important for users 'on the move', who allocate their attention to several competing tasks. Design should facilitate a rapid perception of the relevant information, and support an accurate interpretation of its significance (e.g., estimation of the air traffic flow - under/ over a critical level, or its approximate value). For instance, discrimination of the critical information could be facilitated by suitable use of colour, use of multimedia facilities such as animation, blinking images, the use of sound, etc.

Discussion

When we compare the deviations that could happen in the current system with respect to those that might occur in the envisioned system, a number of considerations come out. In the current system it is a fact that there are situations in which the controller are forced to move around the control room and then they might not have the updated picture of the current situation as all the supporting equipment is basically stationary. In the envisioned system the mobile support should (theoretically) allow the controllers to continuously monitor the system. The possible deviations that may occur in the two systems are rather different: in the first option the controllers, although not continuously informed in real time of every change occurring in the system are perfectly conscious of this lack and might compensate by having "faster" communications with the other stakeholders when they are forced to move around the room. In the envisioned system the controllers should not feel such time "pressure" when interacting with other controllers, but, on the other hand, having the mobile device available could make them feel overconfident on the level of knowledge they have of the current situation. However, having the mobile device might allow better communications with other controllers because the mobile device might be exploited to empower such communications. Then, it is possible to see how changing a particular context component (device) might have effect on issues related to other components in the context (communications occurring in the environment).

Moreover, in the current situation the stationary system allows for having a global picture of the current situation system, whereas the limited capabilities of the PDA provide users with a partial view of the current situation

Conclusions

In this paper we have presented a method that exploits a distributed task performance analysis, which aims to identify potential safety-critical issues through the analysis of deviations from the task plan and the information necessary for its accomplishment. One key advantage of this method is the possibility to support design in safety-critical contexts when the introduction of new mobile technology is considered. This result is obtained because the analysis is able to consider the context and how it can affect the user interaction and the tool is able to generate interfaces that are able to adapt to the feature of the devices considered.

In this way the environment supports the work of multi-disciplinary groups where the result of the conceptual design can be used to actually support the development phase.

Future work will be dedicated to providing tool support for the proposed method.

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