Development and Application of a Universal, Multimodal Hypovigilance-Management-System

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Abstract. States of hypovigilance cause severe accidents. Technical compensation can be provided by hypovigilance management systems (HVMS). In this paper, existing HVMS are discussed and the need for the development of a novel universal, multimodal HVMS is deducted. The development of such a system is presented and its application is illustrated with two application scenarios.

Keywords: HMI, Safety, Sleepiness, Vigilance.

1 Introduction

Human beings need to sleep. Sleep is not a matter of choice, it is essential and inevitable. The longer someone remains awake, the greater the need to sleep and the more difficult it is to resist falling asleep. Sleep will eventually overpower the strongest intentions and efforts to stay awake (NCSDR/NHTSA, 1998).

Today's "24 hour society" seems to pressure many individuals to sacrifice sleep in favor of other activities, without realizing the negative effects this has on their health and ability to perform a wide range of tasks. Sleepiness reduces alertness and with this, vigilance, and attention, so that the ability to perform is impaired. The speed at which information is processed and the quality of decision-making is also affected (Reissman, 1996).

In addition, as much as 10% of the general population suffers to some degree from sleep disorders, such as: hypersomnia, narcolepsy, daytime functioning in insomniacs and sleep apnea (Backhaus & Riemann, 1999). Sleep disorders may cause extreme tiredness, loss of concentration and a pronounced inability to function normally in one's daily routines.

Both involuntary and voluntary sleep deprivation cause the related phenomena of hypovigilance and, therefore, are among the key causes of serious accidents: According to NASA Aviation Safety Reporting System, approximately 21% of the aviation incidents are fatigue-related. In a similar way, most nuclear accidents (among them Chernobyl and Three-mile Island) have clear fatigue-related causes (Mitler et al,

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1988). Moreover, more than 40% of automotive accidents on US-highways can be related to hypovigilance (Garder, 1998).

Obviously, the support of technical systems in states of hypovigilance is desirable. In fact, such systems basically are present and are known under the name of *Hypovigilance Management Systems* or *HVMS*.

In principles, HVMS measure the state of vigilance of the respective user and take according measures if a critical state of vigilance with respect to the work task of the user is reached. On the one hand, the user is warned and informed about his/her state of vigilance, on the other hand the system might try to keep the user awake for a certain time (if at all possible) in order to enable the user to finish dangerous actions (e.g. to get off the road when driving tiredly).

However, it has to be mentioned that the systems known so far are mostly in a research state of development. They mainly base on single-sensor approaches and lack reliability. Moreover, most of these systems are not comprehensive, i.e. they focus on one part of the system, e.g. the sensors and neglect the other elements of a HVMS or include only rough approaches to these. Finally, the systems present are restricted to single use contexts such as the car. However, as was outlined above, hypovigilance is a problem in many different use contexts. Therefore, a universal system is needed (Hagenmeyer, 2007).

Clearly, there is a need for the development of a more reliable system that is universal in terms of its utilizability in different use contexts both with respect to the sensors used and the human machine interface (HMI).

2 Development of a Universal HVMS

Such a system was developed within the Sub-Project 4 of the SENSATION Integrated Project, a 6th Framework-Programme research project, co-funded by the DG Information Society of the European Commission, which aims at promoting the health, safety and quality of life of people and protecting the environment by reducing hypovigilance-related accidents and thus the impact on environment through the application of novel micro and nano sensors and related technologies, of low-cost and high-efficiency, for human physiological state monitoring.

Sub-Project 4 “Industrial Applications” of the SENSATION Integrated Project aims to integrate the developed project sensors in multisensorial platforms and use them to detect and predict human operator hypovigilance to promote safety, comfort and quality of life.SP4 involves three major areas of work:

- Development of hypovigilance detection, prediction correlation and operator warning algorithms.
- Development of multi-sensorial systems for hypovigilance detection, prediction, sleep management and operator warning.
- Verification of the developed applications in a series of industrial Pilots and specification of future research needs.

The innovation of Sub-Project 4 is the target to overcome the limitations and restrictions of the existing prototypes and systems, by fulfilling four major requirements:

- To be autonomous: to provide automatically a diagnosis about the user's state.
- To be non-supervised: interpretation of the diagnosis must be performed by an intelligent decision making module and this information should be displayed to the user without any on-line intervention of an expert.
- To be non-intrusive: this excludes all wired sensors.
- To be able to operate in non-constrained environment: as a consequence, such sensors will have to cope with environmental non-controlled conditions.

2.1 Basic Structure of the SENSATION HVMS

The basic structure of the SENSATION HVMS is depicted in figure 1.

Relevant data for the measurement of the vigilance state of the user is gathered by different sensors. In order to reduce traffic on the system communication network, these sensors include a basic pre-processing of data. The sensors communicate with the central system via defined networks: Sensors used close to the body are connected to a body area network (BAN); other sensors such as cameras on the dashboard of a car are directly connected to the local area network (LAN).

The pre-processed data coming from the sensors to the expert system, in a first step, will be combined by means of according algorithms to a vigilance vector, i.e. a vigilance value on a simple scale augmented by the certainty of this value. The warning strategy is implemented in a decision-of-action-to-take-manager; with respect to the use context, it takes the actual vigilance state of the user into account in combination with surrounding variables such as risk level of the actual situation. The action decided in this way is communicated to the user through the respective HMI-elements, which are connected to the expert system though the same BAN/LAN-structure that serves the sensors.

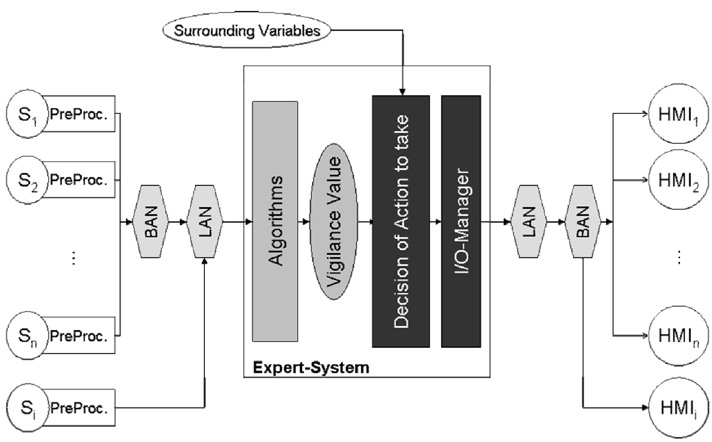

Fig. 1. Schematic of the structure of a HVMS

In the following, the methods applied for the development of the sensory system as well as for the development of the HMI are detailed.

2.2 Development of a Novel Set of Sensors

The HVMS is the central decision system which receives hypovigilance-related measurements from the integrated processing algorithms, which sequentially process signals from a series of novel high-end technology sensors developed within the Sub-Project 2 of the SENSATION Integrated Project and have been selected upon their ability to provide real-time signal processing of physiological parameters related to hypovigilance. Those sensors are listed and briefly described below:

- **STEREOVIEW-EYE sensor.** Video camera platform including 3 cameras for stereovision purpose for different human being supervision application. It includes high performance generation of CMOS camera, targeting driver's eyelid and eye gaze measurement.
- **CAPSENSE sensor.** A capacitive sensor setup targeted at measuring the posture of a seat occupant. The seat can be in a passenger car or the seat of a controller in a plant control room for example. The sensor has the ability to measure whether the seat is occupied at all, if the person is moving on the seat, the head position of the person and some other characteristics.
- **ENOBIO sensor.** Dry electrode for electrophysiology which can be used to measure EEG or other biopotential signals. The novel aspect of this electrode is the electrode skin interface which is provided by a large number of Carbon Nanotubes (CNT) forming a brush-like structure. The aim of this design is to eliminate both the need for gel and the skin preparation needed in traditional electrode applications, hence simplifying the recording of EEG.
- **EARSEN sensor.** It measures the heart beat rhythm, using the difference in absorption taking place when a blood pulse (containing arterial blood) passes between the emitter and receiver of the sensor. Moreover, it includes an inclinometer, from which head position measurements are extracted and processed by an algorithm able to detect head nods, inattention, etc.
- **SEFO sensor.** Thin foil with large area including matrix of sensor elements to be assembled into seat to measure spatial pressure profile exerted to seat and backrest. Seat foil sensor uses porous electret film (EMFiT), which generates electrical charge directly proportional to the normal force. The measurement of charge leads to dynamic principles, however with low corner frequency if wanted.
- **STEREOVIEW-BODY sensor.** It uses the same modules with the STEREOVIEW-EYE sensor but it integrates an algorithm to measure driver activity and posture analysis related to hypovigilance.

2.3 Development of the HMI

In order to scientifically develop an appropriate HMI, the following method is followed:

Firstly, a set of representative relevant applications scenarios with respect to the potential application fields is chosen, including car and truck drivers, locomotive drivers, ship captains and pilots for the transportation sector as well as machine operators, crane operators, process controllers in nuclear power plants and air traffic controllers for the process control sector.

Then, basic requirements categories for the HMI-design with respect to HVMSs are defined. These address requirements and restrictions of the warning strategy, the technical framework, the risk level of the tasks as well as additional aspects, such as the warning not only of the user but of third parties as well. On the basis of this catalogue of basic requirements, all of the chosen scenarios are analysed and, in an additional step, they are clustered to basic requirement groups for warning strategies and HMI-elements. The result of this step of the development process is the deduction of the smallest set possible of basal requirement groups both with respect to warning strategies and HMI-elements.

On the basis of these basal requirement groups, according warning strategies are developed with respect to warning modes necessary and surrounding conditions in order to warn the user as effectively as possible.

Finally, the technical implementation of these warning strategies, i.e. the physical HMI-elements, is developed. Again, the smallest set possible of different HMI-elements is to be designed with respect to the basal requirements and, hence, to the application scenarios.

With the method described above, a multimodal, universal HVMS has been developed which is applicable in all of the application scenarios mentioned:

Upon activation, the system starts in *normal mode* in which a status indicator informs the user about the hypovigilance state monitored and indicates that the system is working properly. Such continuous information should be presented in a way that it is not disturbing the user but should be recallable at any time; a traffic light like status indicator was chosen for this purpose.

The *warning mode* is activated when the user reaches a critical level of hypovigilance. Within this mode, depending on the current hypovigilance state of the user, either a cautionary or an imminent warning is displayed with the aim to stop the user conducting the work task and, by doing so, avoid accidents.

According to Wickens et al. (1998), an effective warning must first draw attention and then inform about the hazard, the potential consequences and give recommendations on how to react. Optionally, a feedback might be required from the addressee in order to confirm the reception of the information. Therefore, for cautionary warnings, the attention of the user is drawn by a complex sound according to DIN ISO 7731 (2002) in combination with a haptic vibration pulse and a bright flash.. Then, more complex information about the hazard, its potential consequences and according countermeasures are presented by means of speech messages. These were preferred vs. text displays because of their higher compatibility with most work tasks in respect of the mobility of the user and interference with the work task itself. Finally, feedback from the user is demanded which is to be given via a push-button. In case no feedback is given, the warning is repeated. If still no feedback is received or if the user reaches a more critical hypovigilance level, an imminent alarm is given which follows the same structure. However, the stimuli to draw attention are intensified by an increased volume, higher pitch and vibration frequency. Moreover, the speech messages are adapted, emphasizing the urgency to quickly react to the warning.

After an imminent warning was given and confirmed, the system switches into the *vigilance maintaining mode* aiming to support the user safely stopping his/her work task, e.g., safely driving to the next exit. The user is informed about the activation of the vigilance maintaining system (VMS) as well as its restricted, short term usefulness by a speech message. The VMS then stimulates the user by means of so called “Landström Sounds”: Landström et al. (1998) showed that specific disharmonious sequences of sounds, each lasting around 4 seconds, that are presented in irregular intervals of up to 5 minutes significantly enhance wakefulness. Moreover, a high level of acceptance by the participants could be observed.

The above warning strategy was implemented as a finite state machine in SWITCHBOARD, a software package developed at Fraunhofer IAO with various I/O-capabilities. It runs on a central computing unit which integrates the sensor signals and, computes a vigilance value and decides about the actions to take (compare to the “expert system” in fig. 1). The sensors and HMI-elements were developed in a close-to-body configuration and are connected to the central computing unit via a body area/local area network. A screenshot of the implementation of the warning strategy is depicted in fig. 2.

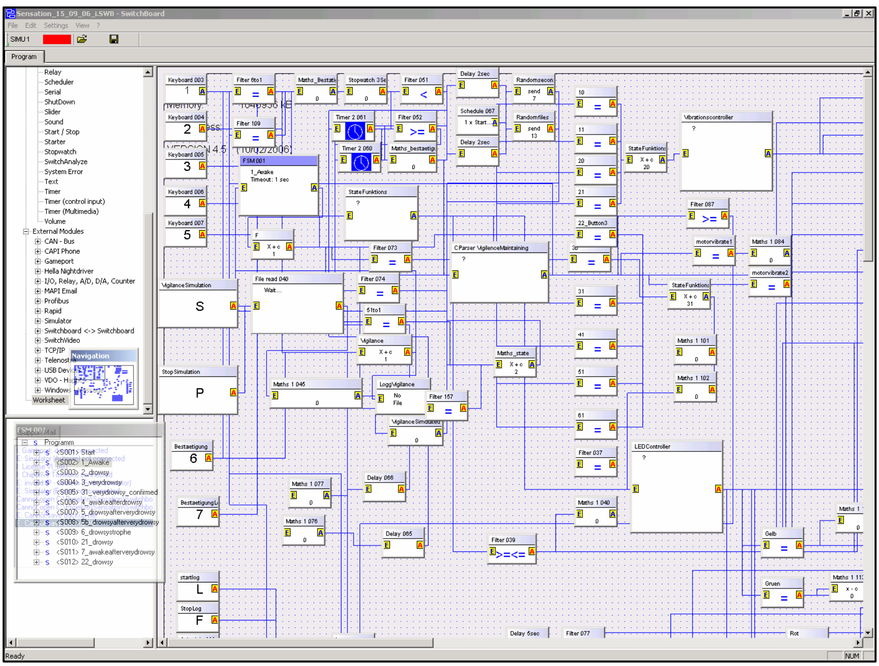

Fig. 2. Screenshot of the SWITCHBOARD-implementation of the warning strategy

The status indicator, visual master alarm and feedback button were integrated in a wrist worn device. (compare to fig. 3; for presentation purposes, all LEDs are activated). Green, yellow and red LEDs were activated according to the respective vigilance state of the user (i.e. awake, sleepy, very sleepy). A flashing white LED in the center of the device was activated in case of imminent alarms. It was integrated in a button which serves for user feedback. Finally, additional buttons for the repetition of speech messages and for volume control were built in.

Fig. 3. Wrist worn HMI-device

Haptic stimuli were presented by a belt mounted vibration device and acoustic stimuli were presented by a standard ear phone.

In this way, a mobile universal system was created. It can effectively be employed in all application scenarios indicated. However, for non mobile workers, the HMI-setup easily can be "translated" into stationary devices in order to achieve a better usability. For example, in a car, the status indicator might be integrated in the rear view mirror or dashboard, the feedback button might be integrated in the steering wheel, the vibration unit could be mounted on the belt and acoustic stimuli might be given by means of the loud speakers.

In the following, two application examples are given, the car driver and the industrial worker.

3 Car Application of the SENSATION HVMS

The Sub-Project 4 deals with a very challenging target; to develop a driver hypovigilance monitoring system that will incorporate the following features:

- Real-time driver hypovigilance monitoring and warning.
- Vehicle-independent, based on driver physiological and behavioural measurements.
- Unobtrusive and user friendly.
- Effective hypovigilance warning and interaction.
- Integrated system using 'smart' high-technology sensors.
- Innovation: driver hypovigilance-related movements monitoring.

To achieve this challenge, an innovative hypovigilance detection algorithm has been developed, which processes hypovigilance-related measurements from a combination of high-end technology sensors developed within the SENSATION Sub-Project 2, presented in Section 2.2 of this paper.

Moreover, the HVMS system of the car application follows the same strategy described within Section 2.3, but incorporates vehicle integrated modules, such as:

- personalized smart-card for driver identification and driving style recording, integrated at the rear-view mirror of the vehicle.

- visual output of the three warning strategy levels, above the smart card reader, also integrated at the rear-view mirror.
- visual output for critical stage warning, visualized at the rear view mirror as a flashing triangle.
- seat-belt vibrator for haptic warning output.
- sound warnings through tones and speech messages through the car speakers.

The figure below, demonstrates the SENSATION driver hypovigilance monitoring car demonstrator setup.

Fig. 4. SENSATION car application HVMS

4 Industrial Worker Application of the SENSATION HVMS

For an experimental evaluation of the HVMS with high practical relevance, a typical work task of an industrial worker such as rim band welding was selected: It is monotonous, has a long duration, has a high complexity, involves working memory, imposes external control on the industrial worker and is often lowly automated. Moreover, these tasks are often conducted in night shifts.

A rim band is a metal component of a television screen. Its function is to counter the vacuum induced tensions in the glass tube, thus increasing strength and safety of the tube. Furthermore, the rimband holding the tube is mounted into the television or monitor housing by means of stackable lugs welded to the rim band.

Welding rim bands and stackable lugs to rim bands are repetitive positioning tasks which are carried out in a three-shift schedule. It requires mobility and is known to produce different kinds of mistakes (Bonnet, 2000).

This work task was reproduced in a controlled laboratory environment (see fig. 4).

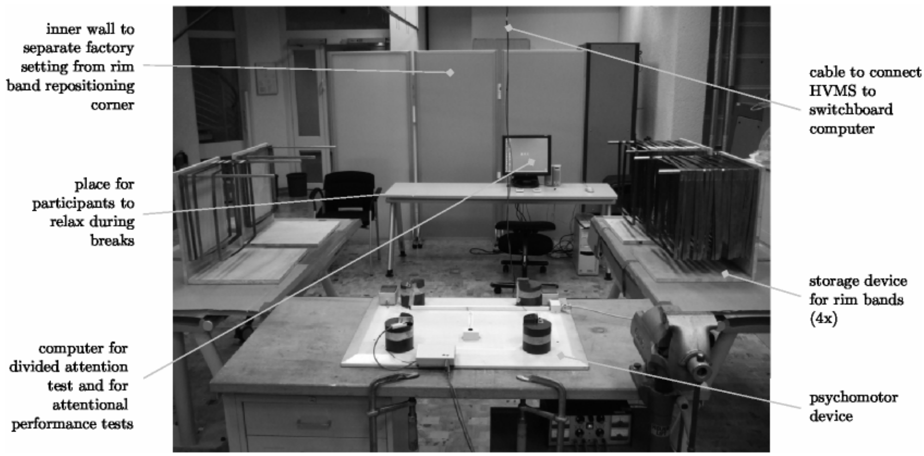

Fig. 5. Setup of the reproduced rim band welding station

Usability experiments were conducted with 24 students. These were divided into three parallel groups which were controlled for sex and chronotype: control group (no warnings), treatment group (warnings of the SENSATION HVMS) and positive control group (random warnings).

A baseline measurement was conducted in the late afternoon. After a night of sleep deprivation, the actual measurements were conducted.

Most participants found the HVMS easy to use (12/13). The functions were easy to learn (12/14) and were easy to remember (12/13). All participants found it easy to understand the speech messages (13/13). The content was clear (12/13) and easy to remember (12/13). Two out of six participants in the random warning group declared that they followed the warning message(s). In the Sensation warning group, five out of seven participants declared that they have followed the instructions. A high compliance to the warnings of the HVMS can be deducted.

The experiment indicates that the use of HVMSs could support hypovigilant workers. However, it should be mentioned that such technical assistance should only be provided when no other countermeasures against sleepiness such as proper shift design and sleep hygiene are effective.

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