Design Requirements Related to Human Information Processing for Detecting People on Camera-Monitor Systems (CMS) of Mobile Machines

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ABSTRACT

According to international standardisation, visual detection of a person is acceptable when he/she is represented in height of at least seven (7) mm on monitors of camera-monitor systems (CMS), e.g., installed in mobile machines for indirectly observing danger zones during machine movements. Unfortunately, neither rationale nor evidence are presented for the measure, no explanations are given how to apply the measure and no contextual factors are considered possibly hampering human detection performance. A research project challenges the measure referring to common sense, accident analysis and statistics, and state of the scientific and technical knowledge and is going to present answers in referring to research findings from science and practice, design concepts and principles in human factors and ergonomics (HFE) and occupational safety and health (OSH) as well as empirical investigations considering requirements for safe operations under realistic working conditions. Initial results are presented to increase awareness of and trigger discussions about an unresolved problem of significant relevance in work domains across industry and services.

1 INTRODUCTION

Human monitoring and control operations are part of many employees' everyday work [1]. This often involves humans carrying out tasks of controlling technical systems, machines, or devices and monitoring human-system interaction interfaces – under conditions designed for a given work system [2]. Such work tasks are performed either continuously, i.e., in control centres in the process engineering industry and in video surveillance operations, or discontinuously but recurring in a varying or occasional manner, i.e., during machine operations in the manufacturing industry or when operating mobile machines at construction sites [3-6].

Introduction of automation by application of assistance systems has the potential, if designed according to human factors and ergonomics (HFE) principles, to optimise human physical and mental workload [7]. However, automation often shifts human task processing towards increasing demands on human information processing and is adding mediating layers between human-system interfaces and distant technical functioning at point of action [1]. Therefore, end effectors are only indirectly monitored and controlled by humans using human-system interfaces such as displays and control actuators with humans often being at remote places under different environmental conditions. This involves actuator-effector data transmission and technical converters (e.g., servo drives) also changing feedback control by replacing or limiting end effector feedback to sensory representations (e.g., two-dimensional view of video representing three-dimensional reality). Consequently, humans may apply mediated control actions and receive mediated feedback (on display).

Even if direct human view to end effectors allows for immediate and unmediated feedback of control interventions (e.g., direct view of the bucket while excavating, direct view of an overtaking car through side window), this is not always possible for different reasons. In some cases, direct view to an end effector could result in physical impairments (e.g., repeated rear-view check by over-the-shoulder glance), is not possible (e.g., read fill level of closed tank), or is not very helpful for monitoring one's own control activity (e.g., temperature control of heating rod in storage tank). In these cases, the human is presented information indirectly via mirrors or displays, often showing digital representations of sensor data, i.e., temperature or fill level displays or display of video camera streaming of rear danger zones.

When direct view into danger zones (e.g., area of risk of collision with persons close to moving machines) is not suitable or not possible, assistance systems such as CMS have been suggested as a measure to avoid collision and to improve safe operations with mobile machines [8]. Presenting streamed view of persons on monitors of CMS higher than 7 mm or at least 10 % of the monitor height is "normally considered acceptable for visual detection purposes" (see B8.2 in [9]). However, increasing concern about the validity of this requirement for safe detection of persons in danger zones has been raised triggered by findings from HFE [10, 11] and OSH [12].

Therefore, the Swiss Federal Institute of Technology in Zurich (ETHZ) investigates the height of persons to be displayed on monitors of camera monitor systems (CMS) for safe detection by operators in danger zones of mobile machines and under operational conditions. This research project [13] is funded by the German Social Accident Insurance (DGUV) and supported several, independent German Social Accident Insurance institutions representing DGUV Expert Committees of Construction Industry, of Trade and Logistics, of Woodworking and Metalworking, of Traffic and the Environment, the German Social Accident Insurance Institution for the public sector in Hessen, and the Swiss National Accident Insurance Fund (suva). The Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA) is involved in research activities during simulation studies investigating significant risk factors and field studies applying activity analyses in parallel with eye tracking under practical operating conditions [13].

2 METHODS

The research project continues along (1) system analysis, (2) simulation studies, (3) field studies, and (4) dissemination of HFE requirements and recommendations for OSH prevention through design. Although the project is still in its early stages, most of the system analysis has already been completed, and simulation studies are currently under development. The primary focus of the system analysis is on Cognitive Work Analysis (CWA [14]) to identify and assess tasks and conditions essential for the safe and reliable detection of persons by operators of mobile machines using CMS [15]. CWA focussed on the first process steps referring, i.e., to the workspace, the monitoring and control tasks and the task processing strategies [16, 17]. The workspace has been described using the abstraction hierarchy method indicating objects, object functions, system functions, values and priorities, functional purpose, and their interrelationships relevant to the work context. Based on procedures applied in previous studies (e.g., [18]), a pre-consolidated version has been discussed with technical experts from different areas (e.g., machine operators, operating companies, designers, and test and certification bodies) in workshops with the aim of identifying constraints, critical elements, and scenarios relevant for designing for occupational safety [19].
Another focus of the system analysis is a literature review. As an ongoing process the review compiles scientific findings from HFE (e.g., [11]) as well as publications and documentations from HFE and OSH related to CMS design and use for the detection of persons in applied contexts (e.g., [20]). The ongoing review also serves project activities like basic investigations on simulation techniques of potential interest for the project [21]) and research for setting up simulation studies and selecting appropriate measures for investigations.
The concept of work system design in HFE structures literature and CWA findings from different sources to be categorised along interdependent dimensions of the concept referring to workers performing work tasks (e.g., safe detection of persons in danger zone) affected by interacting conditions of work organisation (e.g., continuous shift work), workspace and place (e.g., cabin of mobile machine), work equipment (e.g., CMS specs) and work environment (e.g., daylight, frost temperature) (e.g., [2, 22], see Figure 1).

Figure 1. *Operators' glance to CMS (fixation identified by eye tracking) during operations with mobile excavator.*

Critical conditions from a work system point of view as well as constraints and risk factors for person detection on monitors of CMS in the practical work context identified from literature reviews and CWA are collected, prioritised, and selected to be investigated in detail in simulation studies. Study participants will work on tasks in close-to-reality scenarios that are modelled and simulated in mixed reality and virtual reality (VR) setups. This

aims at experimental identification of design requirements for the minimum height for reliable detection of representation of persons on CMS monitors, even under virtually hampered conditions.
Next, the use of CMS under real operating conditions will be investigated in field studies (like in Figure 1). It can be assumed that real environments and a broad range of different situation will allow for comparisons with results of simulation studies and allow for supplementing these with experiences from practical use. Finally, design requirements according to HFE for reliable human detection performance and referring to height of person representation on monitors of CMS are going to be prepared for dissemination (e.g., for standardisation activities).

3 RESULTS

3.1 Potential origin of 7 mm or 10 % for person presentation on monitors

Standardisation for earth-moving machinery on "object detection systems and visibility aids" suggests that persons visualised on monitors of CMS higher than 7 mm or at least 10 % of the monitor height is "normally considered acceptable for visual detection purposes" (see B8.2 in [9]). Unfortunately, neither the standardisation committees nor HFE findings provide information about how these specifications have been established, why they were presented as is, elaborate on factors such as "normally" or provide a comprehensible rationale. However, discussions among OSH and HFE experts resulted in some feasible explanations about potential sources of the specifications and potential shortcomings for establishing rather generic measures without considering variations of operational systems including environments.
First, presenting absolute measures in the given context is rather uncommon and suggests that HFE principles have not been taken into consideration. Humans may appropriately detect objects in visual size, i.e., in the distance of the distal object taken in relation to the visual angle. Therefore, it is required to present object sizes in angular minutes (arc min) to allow for human detection of objects, especially when object presentations vary in distance. This is also why height of Latin characters shall be at least 16 arc min (up to maximum 30 arc min) to enable legibility and about 22 arc min to allow for readability (i.e., about 7 mm at 1.1 m distance [23, 24, 10]. However, measures for legibility of characters cannot be transferred to object detection, since the task of reading characters is different to detecting persons or objects on monitors due to the quality of information presentation, variation in objects, and information required for object detection.
Second, presenting objects or persons at a displayed height of at least 7 mm on monitors of CMS may origin from assumptions about common viewing distances to monitors (see Tab. B.3 in [25]) and normal visual acuity of 1.0 [26], with the latter varying across countries each having specific legal requirements for visual acuity between 0.5 und 0.8 (see sec. 3.2.30 in [25]). However, assessing visual acuity with common procedures [27] requires presentation of Landolt rings in black on highly contrasting white background and at fixed positions. The visual task for Landolt ring identification intends to detect visual acuity and therefore requires ideal conditions for information presentation. This visual task, however, is different to person detection while operating mobile machines and is improper for definition of distal heights of objects on monitors of CMS [16, 28].
Third, the standard presenting minimal distal height for test body presentation on monitors of CMS [9] references another standard for object and person detection [29]. This has since long been withdrawn and replaced by a standard on application guidelines for video surveillance systems for use in security applications [30]. It defines requirements for height of person representation as a function of the human task and display size. Different tasks are defined according to the level of detail that is to be detected with requiring persons' height of 5 % of screen height for monitoring persons, 10 % of screen height for detecting or spotting persons, 25 % of screen height for observing persons, 50 % of screen height for recognising persons, 100 % of screen height for identifying persons, 400 % of screen height (part of full body is presented on monitor only) for screening persons [30]. Required percentages for different tasks are referenced with former PAL analogue monitor resolution and representing a number of pixels for a full body image according to the task and about one pixel per 40 mm object size [30]. An analogue monitor of about 4.5 inches diagonal in 4:3 format with PAL resolution presenting a full body image in 10% of screen height has a distal height of about 7 mm. Since in former times it has been minimum number of pixels specified to enable detecting or spotting full bodies, with nowadays screen resolutions this would require a much smaller size on monitors or 10 % of screen height provides a much higher number of pixels for representing persons on monitor. This idea also exists for character design by dot-matrix (e.g., 7 x 9, [23]). While in video surveillance [30], task performance requires continuous monitoring and specific search for persons, this is not the case in operations with mobile machines when task performance allows for occasional glances for scanning danger zones. Therefore, the requirements given do not seem appropriate and should not provide a reference in a standard for earth moving machines without specific information, supplemental explanations and design requirements.
So far, no other potential explanations for origin of the requirement of a height of 7 mm for acceptable detection of persons on monitors of CMS are available [9]. A HFE perspective is missing, and any design requirement still calls for evidence, especially for an applied context of CMS use in mobile machines.

3.2 Scenarios illustrating relevance for CMS application

Although requirements for CMS design in the standard refer to earth moving machines [9], similar would be helpful for a broader range of machines in different scenarios. Discussions among OSH and HFE experts resulted in a list of different scenarios using CMS for the detection of persons:

- Excavation from shaft for sewer pipe loaded onto lorry with mobile excavator. [20]
- Gate exit of a mobile wheel loader during the transport of wood chips. [31]
- Picking with mobile forklift trucks in a building materials warehouse for groupage transport. [32]
- Moving recyclables and rubbish with excavator at waste incineration plants. [20]
- Grader prepares surface before tarring the road. [33]
- Placing prefabricated bridge components in lock construction with a mobile crane. [34]
- Mobile track construction equipment working at night to replace track switches and rails. [20]
- Tractors with front attachment enter road traffic. [35, 36]
- Manoeuvring a mobile forwarder in the forest for logging trees. [37]
- Right-turning lorry in road traffic. [38]
- Pulling drag buckets on mobile scrapers in preparation of production of fine plaster. [39]

The scenarios selected provide only provide a small impression about potential variability in applications of CMS for person detection in mobile machines. Regarding the concept of work system design, the scenarios reveal some differences across all interdependent dimensions of system design [2]. Also, it could be assumed that some of the differences within each single dimensions call for different requirements for sizes of person representation on monitors of CMS to allow for safe detection. This could be due to different work tasks (e.g., person detection around buckets or forwarder), conditions of the work organisation (e.g., shift work with altering illumination), or conditions of the work environment (e.g., humidity indoors or outdoors, vibrations and nature of the ground), to name but a few. As a result, several risk factors with an impact on human detection performance can be identified for each dimension of system design. The concept of system design may therefore serve a strategy to categorise risk factors to be considered for investigation in simulation studies.

3.3 Literature review structured by concept of system design

Besides CWA the systematic literature review is another part of the projects' system analysis. The literature review aims at systematically reviewing findings from HFE and OSH from scientific and practical perspective. As an initial source HFE handbook and textbooks have been used to identify findings at more generic levels, such as task and equipment design, display arrangement and information presentation design for perception, attentional processes affecting perception and monitor use, and environmental conditions affecting vision (e.g., [40, 7]). In addition, there are individual studies, reports, and notifications of relevance to the given research project. The concept of work system design [2, 22] has been used to cluster findings according to its interdependent dimensions.
The literature review also pointed to a selection of application scenarios for CMS use (see above in 3.2). Regarding work system design, literature also disclosed several factors of relevance that affect the quality of person detection regarding the system design dimension of ***work task***:

- Type of task (e.g., detect, monitor, identify) define object presentation requirements due to granularity of information required for task performance (e.g., [23, 30]).
- Complexity or difficulty of the task varies with task scenario (e.g., [7, 41, 22]).
- Occasions triggering task performance and existing conditions at hand, such as time constraints or concurrent task performance (e.g., continuous monitoring or occasional but intentional checks on monitors of CMS) affect task load (e.g., [42, 22]).

The literature disclosed several factors of relevance that affect the quality of person detection regarding the system design dimension of ***work organisation***:

- Time constraints for monitor checks due to attentional demands of parallel work processes (e.g., [22]).
- Sleep deprivation and shiftwork add demands resulting in fatigue and performance decrements (e.g., [43]).
- Selecting effective colours for improved detection of devices and personal protective equipment (e.g., [44]).

The literature disclosed several factors of relevance that affect the quality of person detection regarding the system design dimension of ***workspace and place***:

- Complexity of outdoor search space (e.g., road construction zone) for object detection (e.g., person) (e.g., [45, 46]).
- Characteristics of persons in workspace to be detected (e.g., figure-background contrast) (e.g., [47]).
- Location, arrangement and distance of monitor related to human vision (e.g., [48]).

The literature disclosed several factors of relevance that affect the quality of person detection regarding the system design dimension of ***work equipment and interfaces***:

- Image quality (e.g., resolution, format, contrast, viewing angle of monitor, camera field of view, frames per second, sensor quality of digital camera) (e.g., [38, 49, 23, 50, 48, 40]).
- Quality of information presentation of video recorded reality on monitor (e.g., [51, 52]).
- Dynamics of information presentation on monitors (e.g., [53]).

The literature disclosed several factors of relevance that affect the quality of person detection regarding the system design dimension of ***work environment***:

- Detrimental vibration or noise have impairing effects on contrast sensitivity and reduce detection rates (e.g., [54, 55]).
- Glare or reflexions of sun light or artificial illumination on monitors result in human error and detection degradation (e.g., [23, 56]).

In practice, factors for each dimension of system design [2] will not occur separately. Usually, factors refer to interdependent dimensions, single factors have effects, and factor combinations often even stronger affect detection performance for persons presented on monitors of CMS. This is the case, i.e., for person detection on monitor of CMS during backward pipe transport outdoors with a mobile excavator in rough terrain during dusk. Since the research project aims at measures for prevention through design enabling safe operations, it is required to first investigate factors separately and next discuss consequences for consideration of factor combinations in practice.

4 PERSPECTIVES

The project started with system analysis, to elaborate on potential risk factors for human detection performance for persons presented on CMS monitors for safe operations in practical settings. The CWA and ongoing literature reviews in combination with regular discussions with HFE and OSH experts revealed a broad range of disciplines involved, of findings of relevance in the given context, and of applications and use of CMS in practice. Results presented refer to potential origin of information given in standards [9], about scenarios of potential relevance for applications of CMS to supplement or replace direct vision for safe operations of mobile machines, and about a structure proposal for categorising potential risk factors for person detection based on the concept of work system design in HFE [2].

Findings of the CWA [19] are currently under discussion among HFE and OSH expert and will be used together with findings from literature review for identification and selection of risk factors under investigation in simulation experiments [15]. It can be assumed that investigations in simulation scenarios will allow for comparisons with results of field studies and for supplement these with experience from practical use. Requirements for a minimum height of person representation on monitors of CMS are being prepared for standardisation activities as well as for prevention through design measures to contribute to safe operations and a reduction of collisions and accidents with mobile machines.

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