Human Centered Design of Mobile Machines by a Virtual Environment

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Abstract. Psychomechatronics is a new holistic discipline that integrates mechatronics and cognitive science, offering innovative methods that lead to the concurrent design of human–machine systems. According to current methods, mechatronics features are designed first and human factors are considered thereafter. A problem with this approach is that it is often too late to impose significant changes in the mechatronics design at that time. Psychomechatronics, on the other hand, takes the nature of human cognition as the starting point of systems design and therefore it is a human-centered design principle. It does not adhere to the conventional sequential approach but applies simultaneously both mechatronics and cognitive science at the same conceptual stage, which optimizes the design of hybrid human–machine systems. The paper presents the key ideas of psychomechatronics design method with special reference to mobile machinery. The required virtual environment for carrying out the psychomechatronics design of mobile machines is described. The paper presents the results of applying usability test in a virtual environment for a sample mining machine.

Keywords: Human–machine systems, Human-centered design, Usability.

1 Introduction

Virtual Prototyping (VP) is becoming a commonly adopted design and validation practice in several industrial sectors. Companies are moving from expensive physical models of designs to digital (virtual) models. Compared to physical models, virtual prototypes are in general less expensive, easily configurable and support variants, and allow for several simulations to run on a single model. Moreover, tests are repeatable, and the results of validation are often immediately available for product design review. Virtual prototypes often provide insights that physical testing would not reveal. Even if VP does not completely substitute physical models, it helps optimizing and eliminating redundancy in test facilities, accelerating life testing, and reducing the overall number of physical models used in the product lifecycle. Today, VP has its main focus on the late concept and engineering analysis stages of the product development process [1].

Recent trend aims at also using VP earlier in the concept stages, when product design is not too much detailed and changes do not heavily impact on the product

M. Kurosu (Ed.): Human Centered Design, HCII 2009, LNCS 5619, pp. 1099–1108, 2009.

development process. Used in the conceptual phase, VPs offer the possibility of evaluating cognitive concepts improving the product quality, and better exploiting designers' activities. For these reasons, this practice is rapidly catching on in engineering design as well as human-centered design principle. Most advanced VP systems are based on Virtual Reality (VR) technologies. Visual techniques have rapidly evolved in the last decades, providing new devices supporting realistic rendering, stereo viewing, and immersive experiences [2]. Conversely, research and development of interactive devices have provided less innovative and effective solutions.

The three dimensional (3D) devices, like 3D mice and joysticks, support a more realistic and intuitive interaction with 3D models [3]. Since a few years, some digital design tools allow users to physically get in touch with the design while working on a computer.

Physical interaction with the new product is considered important because designers can explore the product's shape and style, and evaluate proportions. It is an intuitive modality for modeling new shapes, and for testing and evaluating product functionality and ergonomics [4].

New modeling systems are being developed which allow designers to use their usability skills while working in the virtual environment. The potential of such technologies that allow a less constrained, more natural and intuitive interaction with virtual models has increased the drive towards computer support for the whole design process, in particular for conceptual design [5, 6]. The idea of psychomechatronics design method with special reference to mobile machinery is at the basis of the research work described in this paper. This study aims at developing psychomechatronics design methods and tools for the modeling and simulation of human-operated mobile machines that perform complex tasks in unfriendly conditions. Instrumental to the success of the project is the development of a simulation platform that creates an immersive virtual environment that offers virtual user experience of the real machine.

2 Psychomechatronics

Psychomechatronics is a new holistic discipline that integrates mechatronics and cognitive science, offering innovative methods that lead to the concurrent design of human–machine systems. Psychomechatronics, on the other hand, takes the nature of human cognition as the starting point of systems design and therefore it is a human-centered design principle. It does not adhere to the conventional sequential approach but applies simultaneously both mechatronics and cognitive science at the same conceptual stage, which optimizes the design of hybrid human–machine systems. The major benefit of the psychomechatronics approach is that it enables the development of human-operated machines that enhance the performance both of operators and the machine.

2.1 Mechatronics Systems

A mechatronics system consists of mechanical and electronic components. The function of the whole system, however, cannot be explained fully by the examination of the function of each component because the final function is produced as a result of the interaction of the functions of the components [7, 8]. Fig. 1 shows the interconnections within a mechatronics human-machine system. It can clearly be concluded in the figure that a human driver forms a dynamic system with the machine through his sensory-motor skills. In semi-autonomous, it is often needed to construct artificial stimulation of human sensory functions in order to substitute the natural impacts and loadings of machine to human. Also because the modern machines are more and more fly-by-wire systems it is possible to filter out the unwanted behavior of the driver to increase safety and usability of machine.

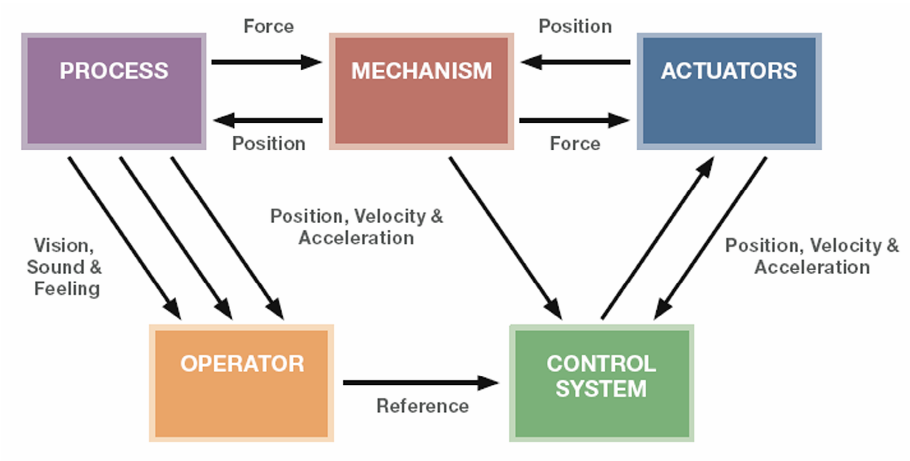

Fig. 1. Interconnections within a human operated mechatronics machine

2.2 Cognitive Science

Cognitive science may be concisely defined as the study of the nature of intelligence. It draws on multiple empirical disciplines, including psychology, philosophy, neuroscience, linguistics, anthropology, computer science, sociology and biology. The experimental research methods in cognition science range from questionnaires and statistical analyses to body tracking, pulse and blood pressure measurements [9]. The experimental research methods in cognition science range from questionnaires and statistical analyses to body tracking, pulse and blood pressure measurements [9]. According to current methods, mechatronics features are designed first and human factors are considered after that. The problem with this method is that it is often too late to impose significant changes in the mechatronics design at that time. To solve the raised problem, we suggest using the dynamics model of mechatronics system in a virtual environment and performing the usability test to find the problems of design. The modified machine is more usable for operators because of applying ergonomic and usability criteria in the design process.

Cognitive task analysis (CTA) is an emerging approach to the evaluation of mechatronics systems that represents an integration of work from the field of systems engineering and cognitive research in machine operating. It is concerned with characterizing the decision making and reasoning skills and information processing needs of subjects as they perform activities and perform tasks involving the processing of complex information [10]. There are a variety of approaches to cognitive task analysis. The approach to cognitive task analysis as described in this paper is closely related to that described by Means and Gott [11], which has been used as the basis for development of intelligent tutoring systems. The first step in such a cognitive task analysis is development of a task hierarchy describing and cataloging the individual tasks that take place during operation of a mechatronics system (with or without the aid of information technology). Once tasks have been identified, the method typically involves observation of subjects with varying levels of expertise as they perform selected tasks of interest. In our studies this has often involved the subjects carrying out the task while using a virtual environment system. Our approach, described in detail below, typically involves video recording of subjects as they work through selected tasks. An important focus of this approach is to characterize how user variation (e.g., differences in users_ educational or technical level) affects the task and the occurrence of potential problems characteristic of different types of subjects studied. CTA has also been applied in the design of systems in order to create a better understanding of human information needs in development of systems [10, 12].

3 Usability

Usability is a quality attribute that assesses how easy user interfaces are to use. The word "usability" also refers to methods for improving ease-of-use during the design process. It is important to realize that usability is not a single, one-dimensional property of a user interface. Usability has multiple components and is traditionally associated with these five usability attributes**;** learnability, efficiency**,** memorability, errors and satisfaction [13, 14]. Usability applies to all aspects of a system with which a human might interact, including installation and maintenance procedures [14]. Usability testing forms the cornerstone of most engineering systems. In the study a combination of two important protocols, think aloud and observation methods has been used.

3.1 Think-Aloud and Observation Methods

There are many possible ways of combining the various usability methods, and each new project may need a slightly different combination, depending on its exact characteristics. A combination that is often useful is that of heuristic evaluation and thinking aloud or other forms of user testing. In the study, combinations of task-based *think-aloud* and *observation* protocols were used. Thinking Aloud protocol is a popular technique used during usability testing. During the course of a test, where the participant is performing a task as part of a user scenario, the participants are asked to vocalize his or her thoughts, feelings, and opinions while interacting with the product.

Simply visiting the users to observe them work is an extremely important usability method with applications both for task analysis and for information about the true field usability of installed systems [13, 14]. Observation is really the simplest of all usability methods since it involves visiting one or more users and then doing as little as possible in order not to interfere with their work.

4 Virtual Reality in Psychomechatronics Design Process

Human-machine interaction has been under intensive research during the last decades [15]. The drawback of existing research environments is that the real products or their physical prototypes are needed in order to carry out tests with real human users. It is then expensive and slow to carry out modifications leading to better usability and user comfort and, on the other hand, better durability, lower energy consumption etc. In order to investigate the human behavior as a part of a mechatronics system such as a mobile mining machine an advanced simulation platform is required. The environment should compose at least of the following subsystems; Immersive visualization, haptic or joystick etc, Mathematical model of the machine, solver for simulating the model in virtual reality environment, sound system, and motion platform for feeling of the real machine motion.

By using the virtual environment the psychomechatronics R&D of a mobile machine can be carried out by applying the following procedure:

1. Preliminary conceptual design of the machine which is carried out by using engineering methods and psychomechatronics knowledge.
2. A real-time dynamic multi-body system model for the machine is built by appropriate formulation of equations of motion to guarantee real-time solution. This model should include description of drive, electronic control system and work process
3. Visualization and sounds from the work process and machine are created
4. A model of a preliminary interface and cabin is created in the virtual environment.
5. Test participants and the proper scenarios or tasks are selected.
6. Cognitive tests are carried out with test participants and the virtual machine.
7. The usability analyses are carried out.
8. Modifications in the interface/machine are proposed and the models are updated correspondingly.
9. Phases 6–8 are repeated until satisfactory results are obtained both from the user's point of view and the engineering point of view
10. The detailed design is carried out and using engineering methods

Fig. 2 illustrates the psychomechatronics design process of a mobile machine in a flow chart form.

It is quite obvious that during the iteration cycles in the virtual world qualitative evaluations of the machine to be developed can be given. Qualitative terms such as 'good', 'comfortable' or 'perfect' can be used in evaluating the virtual prototype. They cannot, of course, be used while using traditional engineering methods that use quantitative terms like vibration amplitude, energy consumption, stress, pressure etc. in evaluating the machine properties.

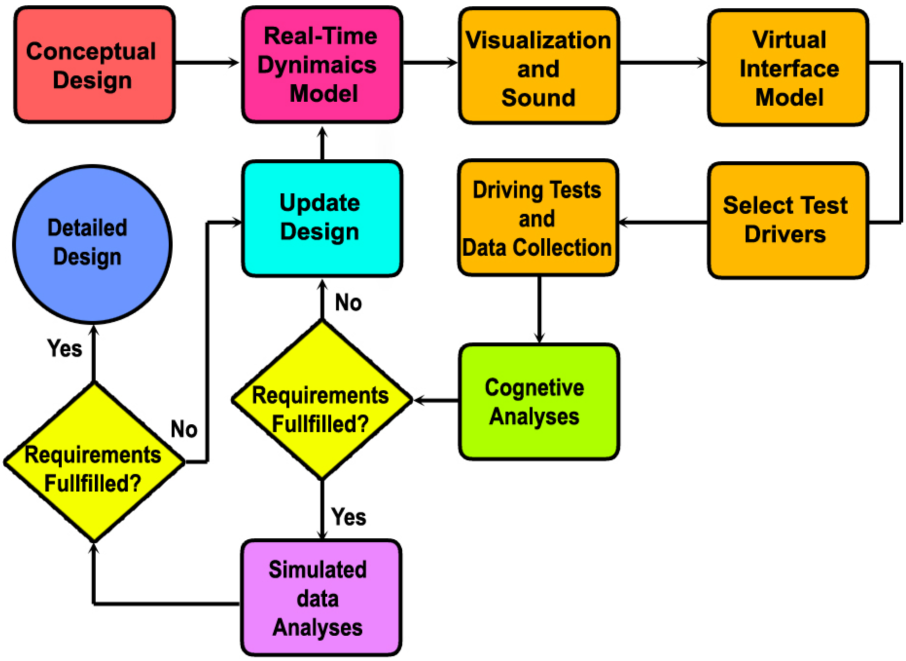

Fig. 2. Flow chart of psychomechatronics design of a mobile machine

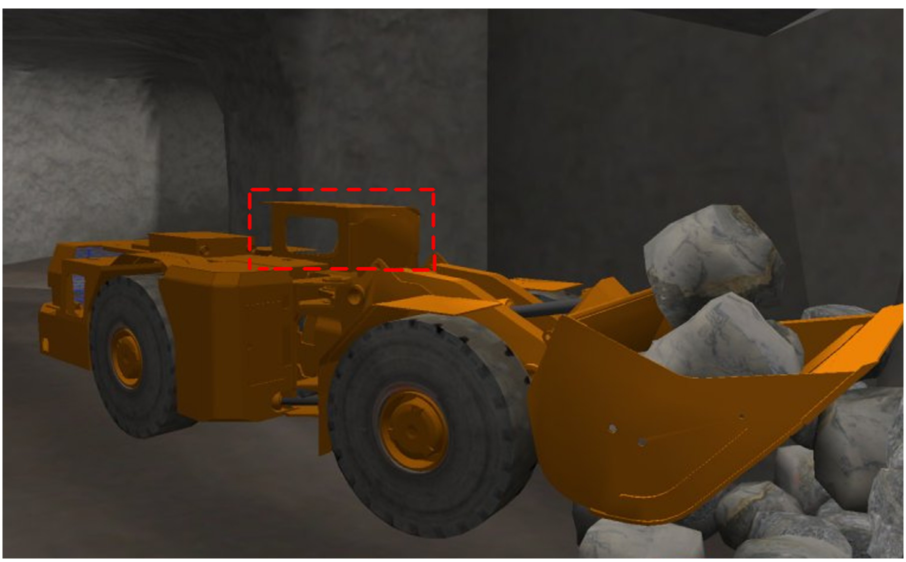

Fig. 3. Virtual model of the loader

5 Mining Machine and Usability Test

The mining industry in the last decade has undergone significant changes with increased mechanization and development of new technologies. Despite changes, human-centered design principles are often neglected in the design and development of new equipment and technologies. This research details a usability study on the operator's of an underground loader, where human-centered design principles are proposed to be considered in the design and development of the new products. The system under study (Sandvik loader LH410) is an underground mining loader with a capacity of loading 10 ton mining stone. Figure 3 shows the virtual model of the loader in a virtual environment.

The loader was design to work in an underground mine. Two different types of buckets are used for usability tests. Figure 4 demonstrate the buckets. Both *barelip* and *shark* buckets has the same volume capacity (4.6 m^3).

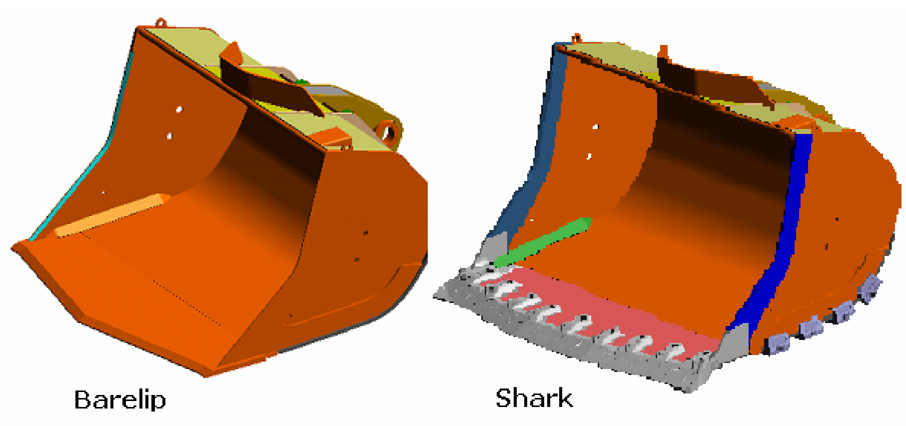

Fig. 4. Barelip and shark buckets

The steering of loader is hydraulically operated. The power steering is controlled by double acting cylinders. The bucket and its boom are operated using hydraulics electric joystick, equipped with piston pump that delivers oil to the bucket hydraulic main valve. The oil flow from steering hydraulic pump is directed to bucket hydraulics when steering is not used.

In Figure 3 a dashed, red line outlines the operator's compartment. From this figure it can be seen that this is certainly not the norm as far as operator compartments of mining machinery go because the operator's seat is in a position perpendicular to the direction of motion and he turns his head to the left when driving forwards and to the right when driving in reverse.

Figure 5 illustrates the setup for the usability test. Three monitors were used to show the *forward*, *right side* and *rear* view of the user inside of the cabin. The joysticks and pedals could move the virtual model of the system the same as the real system in a virtual environment. The virtual simulator was design in Mevea Oy [16].

Fig. 5. Usability test in a virtual environment

The main aim of usability test was determining the success of applying virtual environment for carrying out the psychomechatronics idea in the design process of a mechatronics system. The following subjects were investigated.

A-How much virtual reality is successful in handling design process?

B-How successfully we can apply usability and human factor in virtual environment

C-Applying usability test to find the errors of a designed mobile machine

D-Suggesting the modifications that help the designer during the design process

It takes only five users to uncover 80 percent of high-level usability problems, Jakob Nielsen, [17]. The *virtual simulator* with 5 individuals pulled from the designer engineer and technician users. An entrance and exit surveys before and after each test were taken. Following five tasks were performed in a virtual environment for each individual examiner;

1. Filling loader's *barelip* bucket
2. Filling loader's *barelip* bucket (by means of a camera outside the loader)
3. Filling loader's *shark* bucket
4. Filling loader's shark bucket (using slower lifting)
5. Filling loader's bucket and moving backward to the upper level

All individuals performed each task for three times, the time and the numbers of errors were recorded and video taped. The amount of stones in the bucket was estimated after each test. Following, some of the results are provided;

Using a *shark* bucket helped most of the users to collect 10 percent more stones in their bucket compare to the *barelip* bucket. The reasons for that are the shapes of stones or the effectiveness of the *shark* buckets. Because the seats of operators are in a position perpendicular to the direction of motion and they turn their head to the left when driving forwards makes inconvenience for them, meanwhile they have not clear view of stones and bucket, so attaching a camera on the top of the cabin helped all the examiners to collect more stone in a specific time.

The speed of lifting in the designed model was so fast and the users had problem to filling their bucket. The idea of decreasing speed of lifting to 75 percent during the filling process helped all the operators to load more stone.

The idea of using virtual model of system and the environment for performing usability test is perfect. Several examiners had some comment that are very useful for future progress. In the usability the three monitors were used to show the front, right side and back views from the viewpoint of a user inside of the cabin. It is more realistic, if three screens instead of monitors are used. Meanwhile to feel the movement of the cabin a motion based platform and a real cabin are essential. During the test, the user heard the sound of engine, but it would be more realistic, if the operator can hear the sound of sands and so on.

6 Conclusions

The paper presented the systematic approach referred to as psychomechatronics for designing human operated mechatronics system. The justifications for the presented approach are clearly stated. The main ideas of psychomechatronics are presented and, finally, the virtual environment required for applying psychomechatronics in R&D of a mining machine is presented in detail. In this paper we describe human-centered methodological approach which we have applied for the evaluation of mobile machine designing in a virtual environment. The approach is strongly rooted in theories and methods from cognitive science and the emerging field of usability engineering. The focus is on assessing human machine interaction and in particular, the usability of mechatronics systems in the design process. The paper provides a review of the general area of systems evaluation with the motivation and rationale for methodological approaches underlying usability engineering and cognitive task analysis as applied to a mining machine.

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