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FULL-SCOPE SIMULATION OF HUMAN-ROBOT INTERACTION IN MANUFACTURING SYSTEMS

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ABSTRACT

Human-Robot Interaction (HRI) systems were recently introduced in the manufacturing industry. Robots acting autonomously and working in a direct collaboration with humans create a hazard potential, which is influenced by human factors in complex working situations. In this paper, a concept of a full-scope simulator for HRI applications is introduced, followed by a pilot installation of the simulator. Different environmental influences can be created and repeatably reproduced in an experimental environment within the simulator. The HRI full-scope simulator works completely autonomous and enables comprehensible and repeatable ergonomic proband experiments for an optimal design of HRI systems with regard to human factors and allows for statistical conclusions, e.g., about the human situational awareness.

1 INTRODUCTION

One of the primary goals of Human-Robot Interaction (HRI) is to keep humans and their cognitive abilities as an active link in the manufacturing chain. In connection with Industry 4.0, we see increasing demands on quality, productivity, and flexibility. In parallel, due to the population trends in the majority of the industrialized countries, the skilled staff tends to get older and less available. HRI could be a solution to reduce physical workload of the employees and to improve work content and job satisfaction.

HRI systems have different security requirements, in comparison to industrial robots. The main safety principle of industrial robotics, the separation of humans and robots, is abandoned here. The safety-oriented implementation of HRI systems must, therefore, be fundamentally re-evaluated. The security fences, which were very common in classic industrial robot applications, can not be utilized for HRI systems.

Nevertheless, it is a challenge to layout HRI systems, for ergonomical and physical reasons, but also in respect of a meaningful and satisfying work division between human and robot. Human factor aspects such as attention and situation awareness must be considered as well. Furthermore, safety regulations must be observed.

In this paper, the idea of a full-scope simulator is presented, as an experimental platform for HRI systems. The simulator enables scientific investigations in the collaboration between human and robot, by experiments with several probands. For comparability and proper statistical analysis of the results, the experiments must be carried out with precise repetition and under identical environmental conditions. The goal of these experiments is to gain insights into ergonomic and psychological aspects such as, e.g., situation awareness and to enable investigations with different safety technology. For this purpose, the proven concept of full-scope simulation in power plant technology is transferred to the field of HRI.

2 TAXONOMIES OF HRI

There are three different forms of human-robot interactions (Onnasch et al. 2016):

- *Coexistence* means an episodic encounter of robot and human. The interaction partners do not necessarily have the same goal. The interaction is limited in time and space.
- *Cooperation* means working towards a higher common goal. The actions are not directly linked and do not follow a clearly defined and programmed division of tasks.
- *Collaboration* means interaction and direct collaboration between human and robot with common goals and sub-goals. The coordination of subtasks is ongoing and situational. Synergies should be used.

3 MODES OF HRI

The actual cancellation of the previous principle of the separation of robot and human in industrial robotic applications by HRI systems requires a more detailed consideration of the respective operating mode to the safety requirements. For a safe HRI, four operating modes are differentiated depending on the collaboration space (Barho et al. 2012):

- Safety rated monitored stop.
- Hand guidance with reduced speed.
- Speed and distance monitoring.
- Power and force limitation.

3.1 Safety Rated Monitored Stop

The robot stops if a person enters the collaboration area. As soon as the person leaves the collaboration area, the robot is restarted. Humans and robots share the collaboration area, but do not work there at the same time. A protective fence is not required, but a sensor system must automatically detect the approach of humans. The safety rated monitored stop is suitable for the interaction type *Coexistence*.

3.2 Hand Guidance with Reduced Speed

The robot is guided by the operator, e.g., by means of a handle, which is mounted directly on the robot. The movements and forces that humans transfer to the robot are detected by sensors and converted into an immediate movement of the robot. To increase safety, the speed of the robot is limited. The hand guidance is suitable for the interaction type *Cooperation*.

3.3 Speed and Distance Monitoring

The robot does not stop when a human enters the collaboration area. Safety is ensured by the distance between human and robot. Human and robot work in the collaboration space in the same time. A sensor system monitors the distance between human and robot and the speed of the robot is slowed down when approaching. Contact is not permitted. If a minimum distance is undershot, a Safety Rated Monitored Stop is triggered. A collision is avoided. The speed and distance monitoring is suitable for the interaction type *Cooperation*.

3.4 Power and Force Limitation

A sensor-based monitoring is also involved, slowing down the robot in case of a human approaching. However, contact between humans and robots is allowed. The risk potential is reduced to an acceptable level by limiting the robot's dynamic parameters. For this purpose, the maximum force of the robot and the dynamic performance is limited, in order to guarantee freedom from human injury even in the case of a contact. The difficulty lies in the definition of verified power and force limits for pain and injury thresholds (Huelke et al. 2010). The power and force limitation is suitable for the interaction type *Collaboration*.

4 METHOD OF HRI SIMULATION

The method of HRI requires a special procedure in the planning of applications. For this purpose, a combination of real test environment and simulator is used and referred to as a full-scope simulator. Of course, a large number of simulation methods already exist in the field of robotics. However, these are limited to the questions of kinematics (for example, accessibility of gripping positions) or cycle times, depending on the type of simulation and the application. At best, humans are included in these simulations as a kinematic model of an ergonomics simulation.

In HRI in particular, however, there are also a large number of aspects of industrial psychology that should be the subject of planning for the HRI facility. How is the operator's attention focused on a particular situation? Is there a connection between perception and hazard potential that is relevant in the safety analysis? Such and similar questions can not or not fully be answered with today's simulators. Therefore, in the full-scope simulator, processes of HRI systems including all operator functions are to be completely simulated. These can then be experimented with any number of probands.

So far, full-scope simulators have been used exclusively in power plant technology, especially in nuclear technology. A typical definition from the literature is as follows: "A full scope simulator is a simulator incorporating detailed modeling of systems of Unit One with which the operator interfaces with the control room environment. The control room operating consoles are included. Such a simulator demonstrates expected plant response to normal and abnormal conditions" (NNR 2006, p. 3).

Accordingly, a full-scope simulator is understood to be a simulator that simulates the behavior of the modeled reference system (here in the jargon of power plant technology: Unit One) in order to investigate the operator's interactions with the system. The control elements of the reference system are part of the full-scope simulation. Such a simulator is used to train operators in dealing with the regular and irregular operating conditions of the reference system.

In power plant operation, a constant and effective training of the operators is required. The goal is to drive the power plants safely and efficiently. Full-scope simulators carry out many important parts of the training programs. These training programs are designed to increase the decision-making and analysis skills of operators and prepare them for problems that may arise during operation of the actual equipment (Tavira-Mondragon and Cruz-Cruz 2011). Full-scope simulators are recognized as an effective tool for operator training and are used in particular for nuclear power plants.

By using a variety of different human-machine interfaces, the human is directly involved in the simulation processes. There is a causal relationship between human actions and the resulting system states. In addition to improving operator performance through training programs, full-scope simulators are also used to improve plant and personnel safety, reliability, and reduce operating costs. In addition, industrial and psychological aspects (human factors) are also part of full-scope simulations. These include, e.g., attention control and situation awareness.

5 HUMAN FACTORS AND SITUATION AWARENESS

The scientific discipline of Human Factors is defined as the understanding of interactions between humans and other system elements. These include, in particular, methods, theories, and principles that contribute to the optimization of human well-being and overall system performance (Czaja and Nair 2012). The term Human Factors results from the psychic, cognitive, and social factors influencing socio-technical systems. One focus is on the design of human-machine interfaces, especially on security issues and psychological aspects (Badke-Schaub et al. 2012). Due to the increasing degree of automation, human skills in the system have a different role, for example in the form of control activities. The question arises, which human characteristics, for example in cooperation with robots, can and should be taken into account. Among other things, the topics of environment design, task assignment, and responsibilities play an important role.

Perception is a conscious sensory experience (proximal stimulus with subsequent information processing) caused by a physical, distal stimulus, e.g., seeing, hearing, tasting and smelling, touch, and pain senses. The perception may then be, for example, an auditory or visual process, whereby further channels of perception may also be considered. For the perception of environmental stimuli, they must influence a sensory organ. The receptors of the sensory organ convert the stimuli into electrical signals that are sent to the brain via nerves. The signals generated by the receptors are analyzed and processed on the way to the brain and in the brain itself, until finally a conscious perception experience occurs. Perception-influencing environmental factors that could play a role in a full-scope simulation include, e.g., lighting, noise exposure, and vibration.

A look at the human perception process shows that, at the end of information processing, comprehensive mental models emerge that enable situational perceptions. From the bundle of incoming stimuli only those are relevant to action, to which attention is paid. This selection process is based on experience, expectation or attitudes (Wenninger 1991). The process of how individuals perceive and mentally represent a great amount of information in order to be able to act effectively in a given situation is referred to by Endsley as *situation awareness* (Endsley 1995). Situation awareness is defined as follows: ”The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future” (Endsley 1988, p. 1).

Endsley defines situation awareness as a construct that consists of three levels. Level 1 describes the perception of the elements of the environment. Due to inadequate presentation and cognitive shortcuts, this can lead to misperceptions and wrong understanding of the situation. Level 2 describes the understanding of the situation and deals with errors in the correct integration of the information recording. A lack of mental models or blind trust can lead to wrong predictions and, thus, a wrong decision. Level 3 refers to the prediction of future events. This depends on the expert status of the person.

There are various methods for recording the situation awareness. A distinction is made between direct and indirect procedures. Direct procedures provide direct access to situation awareness, while indirect procedures relate to the process of situational awareness or the outcome of awareness of the situation. To investigate situation awareness, various process measures can be used according to Endsley. These include verbal protocols (thinking aloud), psychophysiological measures (ECG, pulse) or communication analysis. However, such measures are rarely used, because they allow for subjective interpretations or require very elaborate measurement techniques in detecting psychophysiological measures. In objective procedures, the knowledge of the person about the current situation is queried and, thus, the situation awareness is measured.

The *Situation Awareness Global Assessment Technique (SAGAT)* method is used to assess and measure situation awareness. Prerequisite for such an investigation is a realistic simulation environment. The progress in this simulation is frozen at random times. Then, the proband in the system is questioned by an interviewer about his perception of the situation at those times. For this purpose, next to the frozen simulation all information sources are turned off. This process is called *Freezing* (Endsley and Kiris 1995).

6 HRI FULL-SCOPE SIMULATOR

The idea of full-scope simulation is transferred to HRI applications. Here, too, the different human-machine interfaces are to be operated and the human is directly involved in the simulation processes. As a closed simulation room, a modular, expandable small-room system is available. The dimensions of the small space must vary depending on the simulation task. On the one hand, the full-scope simulator is supposed to simulate spatially close cooperation between humans and robots. On the other hand, it is important to be able to adapt the available interior space in the simulator to the respective HRI situation. The requirement for setup flexibility is, therefore, essential in order to be prepared for changing configurations.

Figure 1 shows a sketch of this small-room system. The ceiling height inside is 230 cm. The dimensions of the experiment area are 240 cm in length and 180 cm in width, currently. The dimensions are changeable in increments or decrements of 60 cm by reconstruction. Controllable environmental conditions prevail within the room, in order to study influences of lighting, noise, and temperature or to exclude their influence. The full-scope simulator is used to set up the HRC system to be tested in order to carry out proband experiments under specified conditions. The aim is to obtain statistically relevant statements on situation awareness, perceived safety, and focused attention. Also, the probands' distraction and error susceptibility can be investigated.

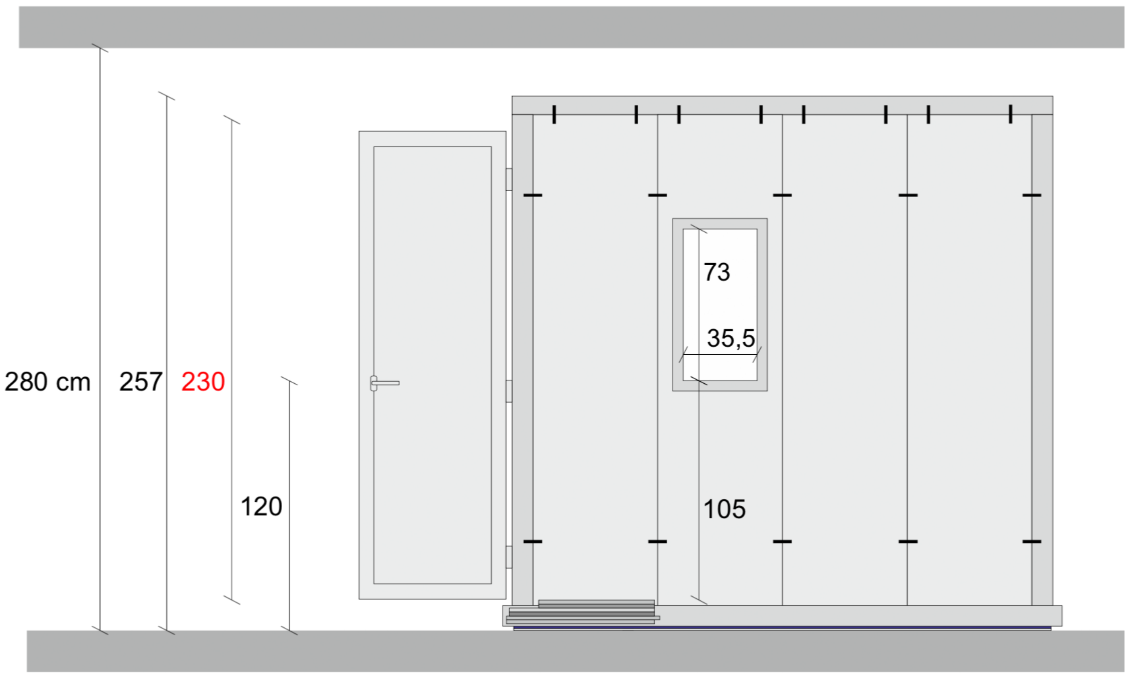

Figure 1: Modular small-room system, view from outside with door open.

The modular room offers the possibility to lead connections to the devices installed inside the room via a cable opening to the outside. This option is used to place control units, control cabinets, and other devices outside the room. In the simulation room itself, devices such as displays, loudspeakers, or lighting installations are installed as shown in Figure 2, numbered as follows:

1. Lighting: Two LED lights are installed in the ceiling.
2. Display: A large display is mounted on the wall, left side of the door. It is used to inform the proband during simulation and may also be used for visual distraction scenarios and industrial background videos.
3. Sound system: For sound reinforcement, four near-field monitor loudspeakers plus a single subwoofer are installed. The audio installation supplies the entire audible frequency range and can be utilized for any audible signals such as background noise, noise contamination, or communication with the proband.

On the front wall outside the room, a control cabinet is mounted. The electrical supply cables from the described devices are connected there, according to the specifications of the test planning, to the system's *Programmable Logic Controller* (PLC). The task of the PLC is the timewise correct switching of the light and sound sources in the box and the monitoring of the protective devices such as emergency stop switch, other switches, light barriers or curtains, and distance sensors.

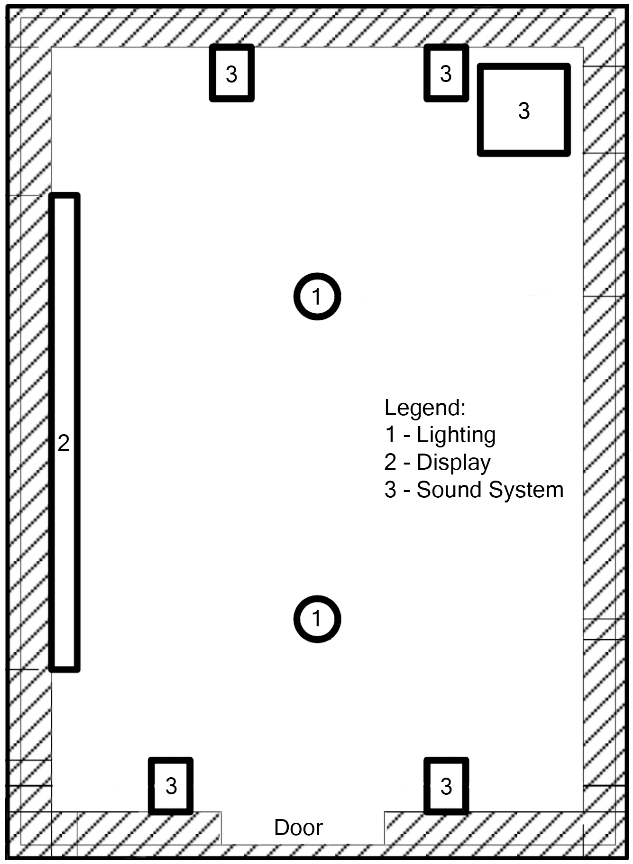

Figure 2: HRI full-scope simulator, sketch from top.

In a typical simulation experiment in the full-scope simulator, two phases are used:

- *Simulation preparation:* Every simulation must always be properly set up and prepared. The simulation room must always be adapted to the respective simulation task. The setup of the experiment is complex and must be well prepared.
- *Simulation experiments:* After the preparation phase the experiments with probands can be performed and documented.

6.1 Simulation Preparation

At the beginning of a simulation project in the full-scope simulator, the task is first of all to define the simulation itself, design it, and put it into safe and verified operation. There are nine individual steps to be carried out for this purpose:

1. *Specification:* Description of the task with consideration of the aspects of modeling.
2. *Formulation of the question:* Defining the desired result by determining the question and evaluation methods.
3. *Configuration:* Adaptation of the simulation room according to the specification.
4. *Construction:* Installation of the robot in the simulation room and building of the workplace including fixture and logistic constructions.
5. *Programming:* Programming of robot and PLC according to the specification.
6. *Test Run:* Check for functionality and feasibility of the simulation.

7. *Verification:* Examination of the suitability of the model with regard to the question from step 2.
8. *Risk Assessment:* Determination of *Personal Protective Equipment* (PPE) and briefing of the experimenter.
9. *Activation:* Release for the experiment series with probands.

At any step, deviations from the specification, technical or ergonomic problems in the implementation, feasibility problems, or hazards can lead to a return to a previous step in the sequence, e.g., to adapt to critical requirements.

6.2 Simulation Experiments

In this phase, the simulation experiments can be carried out. The simulation procedure in a single proband experiment is done as follows in seven steps. This procedure is to be carried out once for each individual proband:

1. *Briefing:* Explanation of the overall context of the experiments (done personally by the experimenter).
2. *Instruction:* Explanation of the procedures in the simulation experiment (depending on specification in person by the experimenter or by media).
3. *Test Run:* Carrying out a HRI task in the simulator under the supervision of the experimenter, if necessary intervening in the process and explanations by the experimenter.
4. *Beginning of Experiment:* Start of the HRI procedure in the simulator under observation by the experimenter.
5. *Freeze:* Planned stop of the procedure in the simulator and questioning of the proband in accordance with the SAGAT method.
6. *Continuation of the Experiment:* Restart simulation.
7. *Interview:* Survey of the proband after completion of the experiment.

The PLC performs a freeze according to the SAGAT method in Step 5 automatically. For this purpose, the process stops, although planned, but unexpectedly for the proband. The lighting is changed to darken the workplace, so that the proband loses the workplace out of focus. Rehearsed noise from the audio system is also stopped. Instead, the proband is asked questions to query psychological aspects to situation awareness. After the questions are answered, the light switches back, the sound or noise comes back, and the frozen process continues automatically. The experiment is continued according to Step 6. The freeze, according to Step 5, can be carried out several times automatically by the PLC, depending on the specification and planning of the experiment.

Figure 3 shows the HRI application in the pilot installation. A height-adjustable work table is set up, which depicts the common working space of humans and robots. On the worktable the devices for assembly, the logistic shelves and devices, the emergency stop, as well as a push button for communication between human and robot are attached.

7 CONCLUSION

In the context of Industry 4.0, we perceive increasing competitive pressure, increasing demands on flexibility, and increasing stakeholder demands on quality. All this happens in the well-known situation of the demographic change in an aging society. New systems in automation can collaborate hand-in-hand with people in production. The aim is to make work contents more diverse, reduce ergonomic burdens, and increase job satisfaction. But how can this be realized? How can work-psychological investigations be meaningfully designed in this context? There are only few experiences and insights available. The situations in existing HRI applications are extremely diverse and, therefore, hardly comparable. Experiments with probands are difficult to realize, because there is no suitable experimental research platform for HRI.

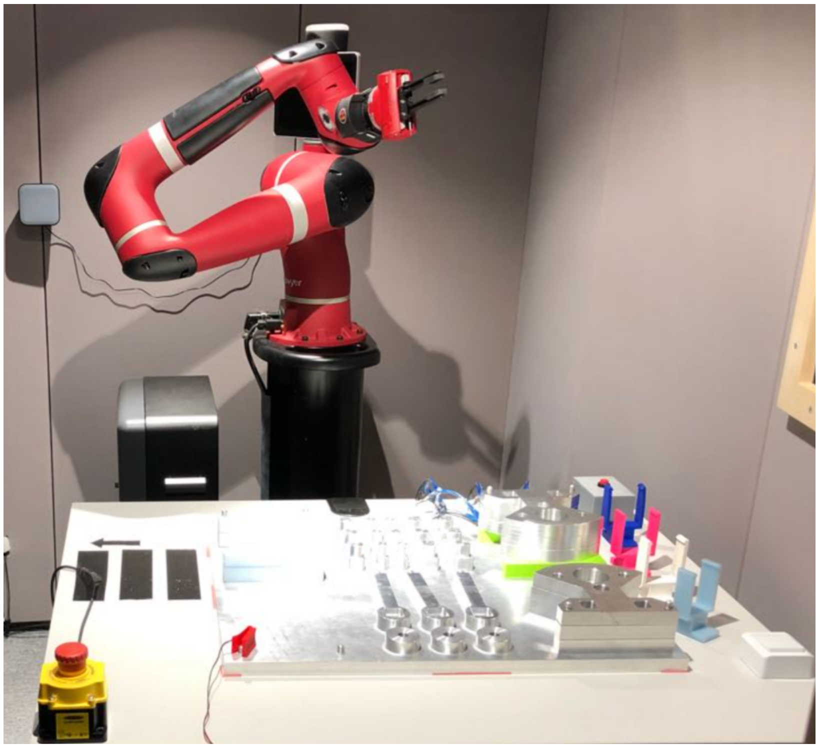

Figure 3: Application inside the HRI Full-Scope Simulator.

In this paper, the idea is taken up and pursued to define a prototype of such an experimental platform, to develop a conception and to carry out the construction. In the future, this platform will allow for experiments with probands under freely definable environmental conditions (such as noise or light) in a real situation, which can be determined by several follow-up experiments. It is referred to here as a full-scope simulator based on comparable applications from power plant technology. Such simulators are used in power plant engineering, e.g., to train operators in handling the equipment.

The scientific background is the idea that in experiments with probands, comparable results can only be achieved, if uniform conditions prevail and the experimental procedures do not vary between probands. Therefore, as a basic principle, the well-known concept of full-scope simulation is transferred to the field of HRI. This concept is the basis for planning the simulator with some essential configurations. The simulator is then set up, programmed, and commissioned in the laboratory using a modular small-room system. The basic procedure for performing a simulation in the full-scope simulator is defined and a pilot installation is described.

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