FULL-SCOPE SIMULATOR FOR ERGONOMICS STUDIES IN HUMAN-ROBOT COLLABORATION

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Abstract: *Robot-based assistance systems are taking on a large number of tasks in the manufacturing industry. Thereby, they are acting more and more autonomously and are also able to work directly with humans in applications of human-robot collaboration. This creates a hazard potential for humans, which is influenced by human factors. In this regard, Situation Awareness (SA) will play an important role. SA is a construct to map the ongoing mental processes of a person interacting with a complex situation. This paper describes the conception of a full-scope simulator as a model of such a system in an experimental environment. Different environmental influences can be created and reproduced in the simulator. With this simulation, disorders and possibilities of attentional control, conclusions about the situational awareness of the probands are expected to be considered. The simulation is completely autonomous and allows an experimental design with several probands. The simulator will also allow comprehensible and repeatable scientific experiments based on the SAGAT method.*

Keywords: HUMAN-ROBOT COLLABORATION, FULL-SCOPE SIMULATION, SITUATION AWARENESS, SAGAT

1. Introduction

Human-Robot Interaction (HRI) aims to keep people and their cognitive abilities an active link in the manufacturing chain. On the one hand, the quality and productivity increase with high flexibility, on the other hand, the skilled staff at the same time getting older and less available. This requires new conditions for direct human-robot collaboration.

HRI systems have different security requirements, in comparison with industrial robots. The main principle of industrial robotics, the separation of humans and robots, is abandoned. The safety-oriented implementation of HRI systems must therefore be fundamentally re-evaluated. The security fences, which were very common in the past, can not be used in HRI systems for reasons of collaboration.

In this paper the idea of an experimental platform is presented, which, in the context of the HRI, is intended to enable ergonomic investigations in the collaboration between human and robot. Experiments with probands under constant environmental conditions can be carried out, to gain insights into situation awareness and to enable investigations with different safety technology. For this purpose, the proven concept of full-scope simulation in power plant technology will be transferred to the HRI. The concept and structure of an HRI full-scope simulator is described.

2. Taxonomies of HRI

There are three different forms of human-robot interactions [1].

- *Coexistence*
  in this context 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 indirectly 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, 4 operating modes are differentiated depending on the collaboration space [2].

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, 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

Here is also a sensor based monitoring involved, and slowing down of the robot in case of human approaching. However, contact between humans and robots is allowed here. The risk potential is reduced to an acceptable level by limiting the robots dynamic parameters. For this purpose, a limitation of the maximum force of the robot and the dynamic performance, 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 [3].

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.” [4]

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 [5]. 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 [6]. 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 [7].

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 as to 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 i.a. 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 [8]. 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* [9 ,10]. 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 [11].

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 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* [12].

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 being 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.

Fig. 1 shows a sketch of this small room system. 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.

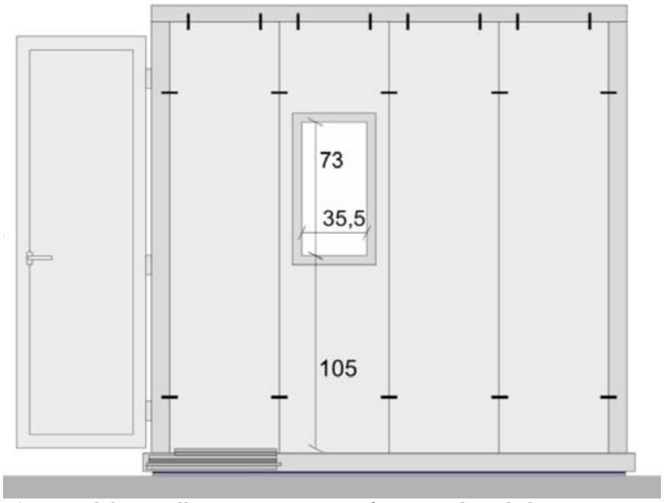

Fig. 1 *Modular Small Room System, View from outside with door open*

The modular room offers the possibility to lead connections to the devices installed inside of room via a cable opening to the outside. This option is used to place control units, control cabinets and other devices outside. In the simulation room itself, devices such as displays, loudspeakers or lighting installations are installed as sketched in Fig. 2. For Lighting two LED ceiling lights are installed (yellow). On the wall, left side of the door, a large display is mounted (blue). The display is used to inform the proband during simulation and may also be used for visual distraction scenarios and industrial background videos. For sound reinforcement, four near-field monitor loudspeakers plus a subwoofer are installed (red). The audio installation supplies the entire audible audio 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 is a control cabinet mounted. The electrical supply cables from the described devices are connected there, according to the specifications of the test planning, to the system PLC. 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.

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.

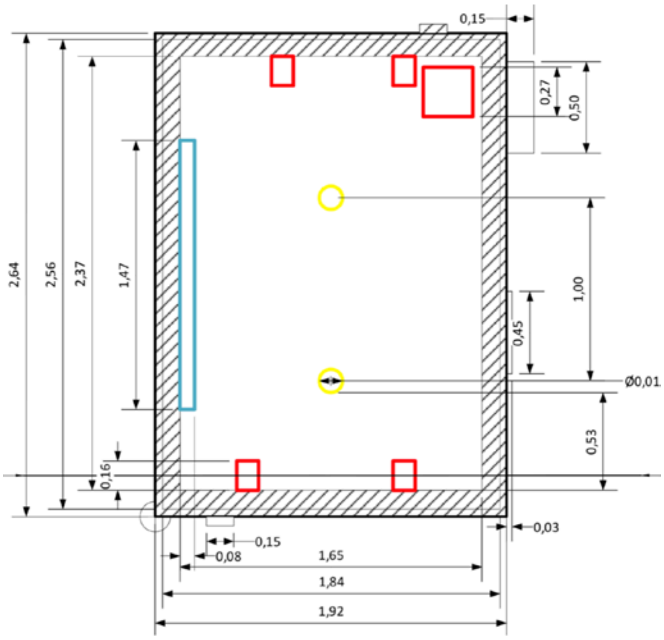

Fig. 2 *HRI Full-Scope Simulator, Sketch from top*

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 9 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 7 steps. This procedure is to be carried out once for each individual proband:

1. *Briefing*: Explanation of the overall context for 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/noise comes back on 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.

Fig. 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.

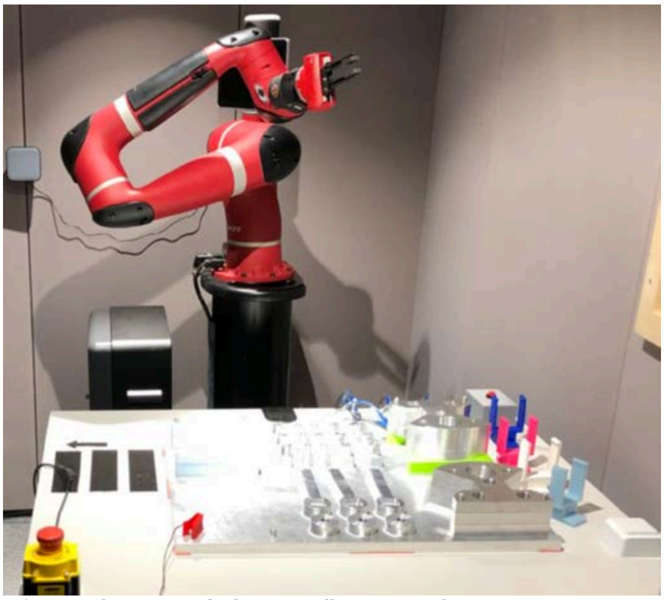

Fig. 3 *Application inside the HRI Full-Scope Simulator*

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 of an aging society. New systems in automation can collaborate hand-in-hand with people in production. The aim is to make work more diverse, reduce ergonomic burdens and increase job satisfaction. But how to do it? How can work psychological investigations be meaningfully designed in this context? There are only few experiences and insights, 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.

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 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. used 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 differ between the probands. Therefore, as a basic principle, the well-known concept of full-scope simulation is transferred to the 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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