Work system analysis for the user-centered development of cooperative mobile robots

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Abstract: One of the main goals of the collaborative research project FORobotics is to gain new insights into human-related aspects and processes that might be essential to the development and effective implementation of cooperative mobile robots. In order to achieve this goal, a qualitative, task-related work system analysis was conducted as a first step. This analysis served to identify potentially relevant context-related aspects that need to be considered in early stages of the development process. Four work systems in three companies were analyzed that included order-picking, manufacturing and assembly tasks. For the analysis, a method was devised based on different modules of RIHA/VERA (Oesterreich, Leitner, & Resch, 2000) and KOMPASS (Grote, Wäfler, Ryser, & Weik, 1999). As such, it comprised document analyses, workplace observations, semi-structured interviews and questionnaires. Further modules assessing technical aspects were developed and added. In a multi-disciplinary workshop, development recommendations were formulated based on the data analysis and taking into account the KOMPASS criteria (Grote et al., 1999) and additional criteria for designing human-machine interaction (Klein, Woods, Bradshaw, & Feltovich, 2004). The recommendations addressed topics such as robot equipment, robot movement and path planning, function allocation and task planning, and interface design.

Keywords: work system analysis, qualitative analysis, human factors, human-robot interaction, applied psychology

1. Introduction: Work system analysis

Industrial workplaces at which people work closely with robots offer the opportunity to combine human skills with the precision and endurance of robots to make production more efficient and at the same time reduce the cognitive and physical workload for humans. Since there are no physical barriers that would protect humans from collisions with the robot, it is necessary to create a usage concept for these workplaces, which does not impact on safety, productivity or user acceptance in a negative way. However, as of yet, systematic research efforts that would provide an empirical basis for the development and employment of worker-friendly cooperative robots are rare. One of the main goals of the collaborative research project FORobotics is, therefore, to gain new insights into crucial aspects of mobile human-robot interaction in industrial work settings (http://www.forobotics.de/, 2017).

Prior to the development and implementation of a new technology, such as cooperative robots, an analysis of the work environment and potential use context is essential. Introducing innovations into the workplace can lead to unintended negative consequences (e.g. Tenner, 1997), such as increased stress levels or reduced productivity (Tarafdar, Tu, & Ragu-Nathan, 2010), in particular, if the use context is not taken into consideration. Rather than investigating specific user characteristics or task requirements in isolation, an analysis of the whole work system, in which the technology is to be employed, is preferable. Work systems, as described in work psychology and ergonomics, are dynamic, socio-technical and highly interlinked open systems (Brauchler & Landau, 1998) that include one or several workers, equipment, functions, tasks and environmental factors within a workspace (DIN Deutsches Institut für Normung e.V., 2016).

Following the user-centered design approach as stipulated by DIN EN ISO 9241-210 (DIN Deutsches Institut für Normung e.V., 2011), research in the FORobotics initiative featured a comprehensive analysis of potential work systems in the production sector, in which mobile cooperative robots might be employed. For this purpose, a qualitative work system analysis was conducted in order to provide recommendations and a basis for empirically well-grounded decision-making for the human-centered development of cooperative mobile robot platforms.

2. Methods

As a first step, an analysis tool kit was devised on the basis of defined criteria. The appropriate tool kit was to provide a conditional work analysis (as opposed to a personal analysis), i.e. the focus should be on the task and environment, not on the investigated workers. Furthermore, the tool should constitute an expert method and not a screening method as the respective activities should be recorded as precisely as possible in order to be able to give well-grounded recommendations. As a third criterion, the analysis should focus on production, assembly and order-picking operations as opposed to office work. Beyond that, the tool should meet basic scientific criteria such as reliability and validity.

2.1 Materials

The devised analysis tool kit was mainly based on the KOMPASS method (Grote et al., 1999) and further complemented by several modules of the RIHA/VERA method (Oesterreich et al., 2000). From both methods, individual modules were selected which were most suitable for the purpose of giving design recommendations for mobile cooperating robots. Both analysis methods are based on qualitative research methods such as workplace observations, semi-structured interviews and documents analysis. The analysis tool KOMPASS by Grote et al. (1999) is theoretically based on a complementary system design approach with focus on human and machine as an interaction with reciprocal dependencies rather than separable entities. The analysis with KOMPASS is based on three levels (i.e. work system, task of human operator and the human-machine-system) and can be used for existing work systems as well as prospective analysis of planned work systems – as it is the case for FORobotics. The criteria for the analysis have been empirically tested with regard to reliability and validity (Grote, Ryser, Wäfler, Windischer, & Weik, 2000).

The RIHA/VERA method (specifically the version which focuses on work conditions in the production sector) is based on the action regulation theory and has been empirically tested through double analyses (Oesterreich et al., 2000). Only modules of RIHA/VERA were used that added information on aspects not considered by KOMPASS (such as non-machine equipment). It thus complemented the KOMPASS method, which focuses on human-machine interaction in more detail than RIHA/VERA. In order to assess equipment, instruments and technical tools in more detail, single modules of RIHA/VERA were modified and extended.

2.2 Analysis Procedure

Three companies in the production sector that aim to introduce a mobile ad-hoc cooperating robot platform into their respective work systems provided access to four different work systems for the analysis. The four work systems included the tasks of production (1 system), order-picking (1 system) and assembly (2 systems) and were all situated in Germany. The analyses were carried out independently of each other by a team of two trained experts as observers with at least two workers each carrying out the same activity. Such a procedure is, according to Oesterreich & Bortz (1994), the strictest method for ensuring a reliable procedure, as it allows to better control the error variances stemming from the observer and the analyzed manufacturer. Thus, each work system was analyzed at least two times with different workers. In total, data of ten workers were obtained in this study. First, qualitative and quantitative data were collected using the tool kit described above. Afterwards, the observation data were validated in semi-structured interviews with the observed persons. After the interviews, the participants were encouraged to ask questions or to add further comments. In consultation with the respective companies, image and video data could be collected during the analysis. In addition, the analysts were provided with company-internal documents for document analysis. The evaluation of the data was carried out according to data protection regulations and only by the respective executing experts.

3. Results and discussion

A workshop on the qualitative analysis of the results was carried out based on the recommendations of the KOMPASS manual. The respective analysts, consisting of a team of two psychologists and a team of two engineers, participated in the workshop. In a first step, a common ground was created by clarifying technical terms and the criteria for a humane design of human-robot cooperation according to Grote et al. (1999, see KOMPASS criteria) and criteria for the design of human-robot teams according to Klein, Woods, Bradshaw, Hoffman and Feltovich (2004), as well as Christoffersen and Woods (2002). Subsequently, potentials and risks for each of the four analyzed work systems were identified from the data by identifying potential contributions from humans and a potential robot system. In a third step, design recommendations were derived taking into account the above-mentioned criteria for each work system.

3.1 Beneficial and obstructive contributions of humans in the work system

Among the identified beneficial human contributions (compared to the robot system) is the performance of more delicate tasks. This had been observed in the case of pre-assembly activities: Rubber seals had to be attached before one of the assembly parts was fitted into a set plate. In addition, changing environmental conditions or unusual new situations were found during observations, with which humans can currently cope better than machines. For example, it had been observed that some under-specified orders or special features of assembly orders required consultation with a supervisor or needed an inter-collegiate exchange. This also includes corrective actions and lack of information. For instance, there were no descriptions on the layout template for the arrangement of set plates, but this could be compensated by the experience of the work force. In addition, humans are able to not only compensate for missing information, but also process different materials and information. Furthermore, non-systematized practices are often found in small and medium-sized companies in particular. In one example, information on the status or location of a product was sometimes passed on to the next worker by a handwritten note at the respective location in the rack ("*[Product number] at [Worker-name] in the assembly area*"). Movable obstacles were frequently encountered. For example, transport trolleys had been parked in the hallway (found in all work systems), people were standing in narrow aisles, work areas were already occupied or product parts protruded from shelves (e.g. in the warehouse) and thus narrowed the way. Human workers are generally better able to identify, classify, circumvent or even eliminate such obstacles than a robot system at the current state of the art.

On the other hand, potentially obstructive contributions of human workers were identified. First of all, part of the variance in the environment was found to be the result of unstructured or inaccurate work and thus caused by humans. For example, discrepancies in the arrangement of workplaces could be found in cases where the arrangement was either not prescribed or where regulations were circumvented. This often led to unnecessary searching behavior, especially at workplaces that were used by several workers. Another hindering aspect of humans can be the consequences of constant under- or overload in the form of performance losses or dissatisfaction. Underload can be the consequence of lacking or low planning and decision-making requirements. In three of the four work systems, at least partial tasks could be identified that only require very little planning or mental effort (e.g. pure sensory motor regulation when arranging individual parts in a set plate) or only minor planning and decision-making requirements, such as the mere visualization of working steps during assembly or commissioning activities. Only in one work system, the planning and decision-making requirements had been found to be moderate, since the adjustment of machine functions sometimes required workers to adjust pre-defined plans. However, overall, planning and decision-making requirements were limited. The tasks thus scored low on the task completeness criterion of KOMPASS. For the evaluation of monotony, in addition to the mental demand, the uniformity and how much the task is capturing the workers attention was examined. One working system was evaluated as at least partially and another as clearly monotonous. Monotonous work could lead to fatigue and may result in errors, and is thus inappropriate for humans.

3.2 Beneficial an obstructive contributions of robots

With respect to monotony, a robot system can contribute positively by carrying out monotonous work and facilitate work in ergonomically unfavorable positions. For example, in one work system, little motors had to be mounted on a steel ring. The steel ring had to be turned around by an electronic lifter, so that the human operator would be able to mount the motors. A robot system would be better able to mount motors without lifting the heavy steel ring, as it can operate in different positions. Also, robotic systems can be used for automated documentation of the quality inspection. It was found that human workers sometimes write down less accurate numbers or circumvent cut-off criteria when the measurement was found to be close to the cut-off. Concerning the quality of work, robots may have beneficial contributions when it comes to accuracy, e.g. in positioning or dosing. In addition to this, quality in structured tasks may be higher, because of more systematic searching behaviors in structured problem spaces. During the assembly task, it was observed that a worker had to go to the warehouse, because an assembly part was missing. A robot would be able to take on such unnecessary walking distances while humans can continue with the main task. Under certain conditions, a robotic system can also serve as an extension of the requirements profile and task spectrum for human workers and reduce monotony.

As a negative consequence, the allocation of functions to robots can also reduce the completeness and variety of tasks by the sole allocation of monitoring or troubleshooting activities to humans. This is the case when the robot system takes over the main tasks and the human operators' tasks are limited to checking the system and correcting errors if necessary. Then again, the monotonous activity is only shifted, when the human worker is only busy with assembling those parts, with which the robot system cannot cope. Finally, it should be noted that a robot platform itself can be a source of error. As mentioned above, aisles were often found to be narrow and a robotic system itself can thus be an obstacle for the human operator, especially when it only moves slowly because of safety reasons and hence is slowing down the human operator. Robots have also oftentimes difficulties in unstructured environments and handling complex materials. For example, in a company with a small production batch but a big variety of the products, a lot of different materials had to be handled including heavy and bulky pieces with sharp edges. A transportation aid especially of products of such kind would be of assistance for humans, but cannot necessarily be accomplished by robots yet.

3.3 Design recommendations and summary

Based on the identification of beneficial and obstructive contributions of human and machine, specific design recommendations for the subsequent development of mobile cooperating robot platforms in FORobotics were derived. Concerning the abilities, the robot system should be able to locate, grab, handle and transport different materials in different orientations and positions or in confined spaces. Furthermore, it should have the ability to overcome small steps and to carry out swiveling movements in a small space. Regarding function allocation, it was found that monotonous tasks are not easily allocated to robots, without shifting monotony or running the risk of restricting the completeness of work. Furthermore, for joint planning activities, it would be advantageous if the system could explain plans to the worker, as s/he sometimes asked for more information in special cases. With regard to the human-robot interface, it should be taken into consideration that in most environments, safety devices such as ear protectors are used due to noise or gloves due to sharp-edged materials, which limits the ability of the worker to communicate with a system to certain channels. Therefore, an interface based on speech input is less suitable and touch screens must also be well considered. Communication via gestures or movement cues would be more suitable. Clearly, the robot system should provide missing information that would otherwise be lost when using the system. In the case of robotic work in unfavorable positions, for example, human operators may lack information about the progress of the process. Finally, it has to be mentioned that a negative attitude towards robots in general (e.g. fear of change in work practices) became apparent in the unstructured interviews. This points to the importance of accompanying the introduction of new technologies, such as cooperative robots, with appropriate change management procedures, if this technology is to be introduced into existing work systems successfully.

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