Physical and psychosocial safety and risk assessment of a mobile robotic industrial co-worker*

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***Abstract*— This paper is a field report about the risk assessment of a mobile robot co-worker designed for real-world industrial scenarios in the LOCOBOT project. Ergonomic and economic criteria for selecting beneficial robot applications induce requirements for robot design. These are especially challenging in the context of safe collaborative robots and the respective regulatory framework. Besides the analysis of physical risk, the importance of considering the psychological and social impact of the machine in human-centered robot design is especially emphasized. Preliminary mitigation concepts are presented.**

I. INTRODUCTION

The use of interactive assistive technologies is of special interest, where robot and human skills can be combined efficiently. Combining dexterousity and flexibility on the human side and precision, repeatability and strength on the robotic side is an especially promising approach for future manufacturing environments [1]. We stress here the effort to introduce robotic co-workers to industrial settings, in particular automotive assembly domains, as pursued by the EU-project LOCOBOT. In car manufacturing, a steady trend toward mass customization and decreasing time to market was encountered during the last decade. While efficient automated and semi-automated processes are widely implemented in modern assembly lines, actual automation solutions cannot provide the required level of flexibility [2]. LOCOBOT provides a solution to this problem by developing a flexible robotic assistant platform (mobile manipulator) to support manual production processes and increase the productivity and precision of such tasks. A further important goal of LOCOBOT is the improvement of ergonomics in industrial production processes [3]. With regard to ergonomics, the use cases exemplify improvements for two different situations that are physically demanding and potentially harmful for the workers health, the lifting of heavy loads and repetitive movements. Moreover, acceptance of the technology is a key issue for successful introduction which requires an in depth analysis of the social and psychological impact. This paper presents a field report of the necessary preliminary physical and psychosocial risk assessment within the boundary conditions of industrial requirements, regulatory framework and guidelines. For this purpose, the criteria applied for scenario choice are outlined. An exemplary ergonomics evaluation is used to quantify the impact of the robot assistant in the respective task. Following a short overview of the considered standards and guidelines, the major risks induced by the required robot design and respective mitigation concepts are presented.

II. CRITERIA FOR APPLICATION SELECTION

The usage of robotic assistants in industry is constrained by the economic value as well as the health improvements for the human worker that can be achieved in the respective task. [2] specifies the following criteria for beneficial application of robot assistants:

- Need for a frequent area restructuring.
- Handling of components with a mass higher than 5 kg.
- Assembly processes with a long distance approach.
- High variety of parts that are delivered sorted.
- Requirement to work interactive with/or near a human.

Many applications in automotive assembly fulfill at least a sub-set of the named selection criteria. Tasks in the given domain that are especially suitable are logistics applications like sequencing and pre-sorting tasks of heavy components as well as more complex assembly task with heavy payload or unergonomic posture. For conformity of a single robot system with the entire range of tasks, a payload of 20 kg and a workspace of 1.8 m have to be supplied. These requirements result from the standardized industrial environments, regarding for example heights of shelves or conveyors, box dimensions, or the average weight of handled parts [2].

Following this rationale, two pre-sorting scenarios and a challenging assembly scenario are chosen as use cases in the LOCOBOT project. The parts handled in the scenarios are high payload items like batteries and starters. An analysis of the achievable ergonomic improvements was conducted, results will be presented in the following section.

III. PROOF OF ERGONOMICS IMPROVEMENT

The preliminary ergonomics evaluation considered the two main issues for muskulo-skeletal injuries and affections: heavy loads lifting and repetitive movements. The NIOSH and the OCRA methods were used. The NIOSH [4] allows the evaluation of different postures and angles of lifting for heavy loads. The OCRA [5] is used to analyse and evaluate the effect of work tasks, involving repetitive movements of the upper limbs. It includes physico-mechanical factors such

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as weight of object, force needed to perform a task, awkward posture, height of the limb when performing a task and also ”environmental” factors such as the possibility to take a rest or the possibility to recover delayed tasks within work time.The role of the LOCOBOT in the three scenarios is to to manipulate and lift car starters and car batteries and thus relief the worker with regard to repetitve movements. Without the LOCOBOT, the worker is allowed to perfom those tasks up to two hours. The robot effect was evaluated under the assumption that in 2% of the cases the human has to assist due to robot failure (3 out of 120 picks/hour for the starters, 2 out of 60 picks/hour for the batteries). Other worst case assumptions are about the height and distance of the object to be manipulated. Both for female and male worker the OCRA and NIOSH assessment showed that using the robotic cooperative assistant the tasks have a very low risk and can be performed for a full 8 hours working shift.

IV. Regulatory framework for collaborative robot design

Introducing robot assistants to industrial manufacturing presents a conflicting situation. While the robot assistant can relieve part of the human physical effort and related stress by improving the ergonomics, the robotic platform adds risks and potential harmful interactions related to the nominal use and potential misuse of the new technology. This is especially challenging given the industrial boundary conditions as specified in Section II. Current state of the art in sensitive manipulation (e.g. UR10 or Kuka LWR 4+) implies that payload and workspace requirements contradict an inherently safe mechanical robot design. Moreover, the level of aversion of a human worker towards the interaction with an intelligent machine can hardly be estimated in advance due to missing evidence. Thus adoption of an autonomous collaborative robot in the work environment notably involves cognitive workload and psychosocial factors that must be evaluated. Such psychosocial risks are part of the work-related-stress. They are known to cause emotional reactions beyond physiological level up to the development of a condition ranging from basic symptomatology, such as irritability or sleep problems, to more relevant problems such as anxiety, depression or burnout syndrome. Psychosocial stress has been demonstrated to lead to an increase of absenteeism and physical complaints. Protracted exposure to stress can therefore have serious negative consequences for the individual, and lead to a loss of well-being. These aspects are of huge importance when making practical decisions on the design of the Human- Robot Interaction (HRI) framework.

This section gives an overview of the standards and guidelines that were accounted for in the risk assessment procedure, for the physical safety on the one hand and for mental aspects (psychological and social factors) on the other hand. Each standard is cited in its respective version at the time the risk assessment was conducted though newer versions might be available by now.

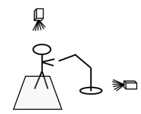
Application Type	Description	Safety Measures	Application Area
Collaborative workspace 	• Autonomous mode within shared workspace • Robot reduces speed and/or stops when person is present or enters workspace	• Sensors for detecting presence of persons (single or multiple sensors) • Adapted velocity according to distances • Emergency stop when prohibited zone is violated, automatic restart when required safety distance is reestablished	• Collaborative assembly • Collaborative handling • Service/ maintenance

Fig. 1. Collaborative workspace and corresponding safety measures according to ISO 10218-2 [9].

A. Physical Safety and Health

Safety is the primary concern when introducing assistive mobile robots in car assembly, as a strict workspace separation is not suitable anymore. For any kind of machine a risk assessment according to ISO 12100 / ISO 14121 has to be done. ISO 12100-1 [6] gives an overview on potential hazards (e.g. mechanical, electrical, thermal etc.) which are further detailed in ISO 14121-1 [7]. ISO 12100-1 defines the risk minimization strategy. The basic rule is that safety measures taken in the design phase are always prior to measures that have to be taken by the user (e.g. personal protective clothing) since they are more efficient and reliable. First of all, it should be tried to reduce risk by inherently safe design. Risk that cannot be eliminated has to be minimized by additional safety measures and, if there is still a residual risk, by user information. Also, any danger caused by the additional safety measures has to be comprised within the risk assessment process. Risk assessment is an iterative process, the detailed steps are given in ISO 14121-1. The standard also specifies the information that has to be available for the risk assessment process. Hazards specific to industrial robot and robot integration can be found in ISO 10218-1 [8] and -2 [9]. Furthermore, specific requirements for collaborative use of robots in shared workspaces can be found there (see also Figure 1).

As the COBOTS standard ISO/TS 15066 is still under development, the BGIA (German Institute for Occupational Safety and Health) is considered [10]. In addition to the ISO 10218-1/2, the guideline contains standard values to keep severity of injuries in case of collision at an acceptable level. The guideline defines thresholds for clamping force, squeezing force, impact force, compression and surface pressure depending on the respective body part. It is necessary, according to the guideline, to specify the parts of the body that might be exposed to the risk of a collision. Also, it would be necessary to conduct tests, assuring that the robot meets the limits of allowable forces and pressures given in the guideline. A corresponding procedure is described in the guideline.

B. Mental stress

As pointed out before, the new technology could impose an additional psychological workload acting as a cognitive and emotional stressor. All of these aspects shall be considered at an early stage of design. Employers are subject to an obligation to take care of work-related stress through the Framework Directive 89/391/EEC on the introduction of measures to encourage improvements in the safety and health of workers at work in the EU. Let us quote point 2.D of the Directive: ”adapting the work to the individual, especially as regards the design of work places, the choice of work equipment and the choice of working and production methods, with a view, in particular, to alleviating monotonous work and work at a predetermined work-rate and to reducing their effect on health.” Three other European directives refer to the need to consider mental stress when assessing risks in specific circumstances. Council directive 90/270/EEC, Council directive 92/85/EEC and Council Directive 2010/32/EU. This legal framework puts work-related stress within the legal framework of occupational safety and health. Work-related stress is to be approached systematically as we do with other health and safety issues, as part of the safety and risk assessment and of the related risk prevention, mitigation and management model. Emphasis should be on preventive actions.

V. Assessment of physical risk and mitigation

Since there is no standard particularly addressing the risk of mobile service robots, the sources of hazard described in ISO 12100 and ISO 14121 are taken into account. Risk evaluation has to consider the most probable but also the highest possible risk, even if the probability of occurrence is not very high. According to ISO 14121-1, risk is a function of the extent of loss (severe injury, lethal injury, one person harmed, several persons harmed etc.) and the incidence rate. The risk estimation aims at determining these for each hazard or hazardous situation. In order to make the processus clear and comprehensible, the mobile robot is divided into 5 modules:

- Platform
- Manipulator
- Gripper
- Sensors
- Environment / Process

Each module is analyzed for potential sources of risk with regard to ISO 12100 and ISO 14121 and under consideration of the specific requirements of ISO 10218. Each possible hazardous situation is analyzed for its possible level of injury and probability of occurrence for each use case. The risk assessment is based on the information available at the very early stage of the project (e.g. Process descriptions of the three demonstrators, Description of robot modules, additional information from project partners). The risk analysis shows that mechanical hazards as free impact and crushing are the major concerns. For the sake of brevity, detailed results are omitted. The contingency plan defines the intended way of making the system safe and assuring physical integrity to human co-workers. It corresponds to the specific hazards derived during the risk analysis. The mitigation strategies focus solely on the operation phase of the robot. Due to the prototypical setup of the robot, other phases of the life cycle (e.g. maintenance, dismantling or assembly aspects) are presently not considered. The most important issues caused by the industrial requirments as desribed in Section II are as follows: due to the high payload, only horizontal movement of the arm (in the SCARA configuration) will be compliant. The strong vertical movement still bears a high risk of injury and requires an additional sensory solution. A pre-collision strategy based on the sensor input and the application of risk measures (e.g. [11][12]) enables speed reduction adapted to human proximity and will as well be responsible for gripper surveillance. Platform requires a special focus on stability compensating for the tilting moment generated by the manipulator arm given the large workspace and high payload and the small platform design due to workspace limitations. Mitigation proposals include a self balancing unit compensating for the tilting moment via the motion of the battery pack inside the platform or an active suspension.

TABLE I
Psychosocial risks and preventive measures

Issue	Stressor	Preventive measure
Peer pressure	Feeling dumb if interacting with a robot	Enable a capacitating social environment
Demographic	Perceptual and cognitive deficits of older workers	Design of HRI and interfaces considers the older worker
Cognitive workload	Adaptation to workflow	Design of interaction and interfaces adaptable to personal cognitive styles
Frustration	Failures in task completion	Arousal and pleasure are included in design, Worker can override autonomous mode anytime
Anxiety	fear without a menacing physical object	System providing continuous information about status of the robot, and about task performance
Fear	Emotion related to a real harmful object	Speed and accelerations, paths, noise, alerts, warnings, have tp be designed to increase confidence
Boredom	Delays and slow reactions of the system	The design includes HRI as part of the workflow
Nuisance	The system appears to demand too much attention or interferes with work	Use of a simple set of commands (20) to execute all the actions and tasks. Once initiated a tasks no more attention is needed by the worker
Perceived usefulness	If high, it creates positive feelings	HRI nested in the tasks and workflow, the worker maintains its role but released from physical stress
Robot overtasking	Diminish self-esteem of the worker	Adequate role of the human thanks to HRI in the tasks/workflow
Robot undertasking	Robot would possibly be felt as a handicap	Robot has relevant role with regards to handling and lifting objects in the tasks/workflow

VI. Assessment of psychosocial risk and mitigation

In the LOCOBOT project we built a rationale based on an extensive and detailed list of issues and related technological features of the robot and the working environment. Adequate preventive measures against psychosocial risks were defined. A summary containing the most important aspects is presented in Table I.

VII. Conclusions

This paper has reported experiences made during the risk assessment of a robot co-worker. Besides the assessment of physical risk, psychosocial aspects are considered equally important. Considerable physical risk amounts from the high payload requirement in the respective application scenarios of the LOCOBOT project. The collaboration with an intelligent robot presents a considerable impact on the working conditions of the human. Measures for accommodating the robot to the human environment and the task have to be taken.

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