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Getting a GRIP on Safe Interactions with Robots

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Abstract— **The paper provides a high-level description for a robot safety management system: GRIP. Originating from a systems-approach based human-robot interaction modeling, the GRIP approach uses digitized questionnaires processing techniques to support end-users in developing a robot safety management system for working with robots and cobots. The GRIP approach combines validated scientific and industrial tools and knowledge into one intuitive product that regards safety from multiple perspectives. GRIP was, and will continue to be, applied on several industrial use case to test, validate and improve the processes and tools.**

I. INTRODUCTION

One of the facets of Industry 4.0 has been the introduction of collaborative robots, or cobots, to the work floor. This effectively re-introduces industry robots into a shared workplace with the human employee. As such, the need arises to readdress the occupational safety issues that had been solved through separation of human workers and industry robots. In the scientific literature, a lot of attention is given to technological solutions to make human-robot interaction (HRI) safer and more efficient [e.g., 1,2]. However, the human factors and occupational safety and Health (OSH) side of HRI has received sparse attention with respect to the functional and operational side [3,4]. One notable exception is the framework developed by Neumann and colleagues to assess the impact new technologies on human workers and efficiency to support further development of such technologies [5]. This paper addresses this gap by introducing a method for the safety management of human-robot interaction with a strong emphasis on the human factors (HF) and occupational safety and health (OSH) side of the interaction.

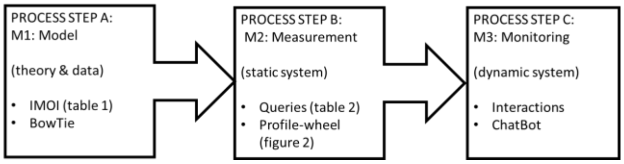

Figure 1. The 3M: Model, Measurement and Monitor.

This paper addresses a structured development method for the digitalization of safety management systems for robot/cobot safety in an industry setting. The method is referred to as GRIP: Guarding Robot Interaction Performance. The method progresses beyond our earlier work [1] by adding digital tools for safety management for robots and cobots. Overall, three steps can be identified in the development of GRIP, to which we refer as 3M: Model, Measure and Monitor (see Fig. 1). The first step is the development of a safety meta-model; this we refer to as step M1. The second step is the development of a (digital) measurement instrument; this is step M2. The third step (M3) is the development of monitoring systems to ensure that safety levels are maintained at an acceptable level. This paper gives a brief description of these three phases and the tools that are developed for them.

This paper starts with M1 which follows from our earlier work on canvassing out relevant safety factors for robot safety. After that we treat a measuring method based on questionnaires for M2; the profile wheel. Then one solution for a measurement (M3) is treated: a bowtie. The summary and conclusion demonstrate how the method is flexible and suitable for local adaptation.

II. SYSTEM DEVELOPMENT WITH M3

A. M1 Safety model: IMOI

The method starts form a holistic model for robot safety to capture relevant influencing factors (M1). The reason for selecting a holistic method is to cast the web widely in to try and capture all relevant risk factors in robot safety. A comprehensive publication was released [1] so this paper *focusses on the main facets in the design of the human-robot* interaction model.

The holistic human-robot interaction model aids organisations in making the human-robot interactions safe, sustainable and efficient for the human worker. It also takes the relevant aspects of the robot and the environment into account. The complete model resembles what is presented in table 1. It can be explained best by highlighting its two main facets.

The first facet addresses a system-approach for interactions and that contains a huge suite of risk-influencing factors. In order to model these factors, model is based on the input-mediation-output (IMOI) model [7, 8]. Originally developed to model teamwork, the input (I) concerns characteristics of team members, the task and the environment which would affect the cooperation. In our work, this was translated into characteristics of the human worker, the robot, and the environment, based on Reason's [9] taxonomy for safety influencing factors: human, technical and organizational aspects. This was a sensible adaptation because Reason's work is better known in the safety domain. The mediators (M) are the conditions or states that emerge from the interaction as a result of the input factors, and which will affect the output. The output (O) concerns the desired results of the interaction (I) and which can directly affect the input for the next interaction. Consider, for example, how successful interaction would

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TABLE I. THE MEDATORS IN IMOI

	Human Input	Robot Input	Environment Input	Mediator	Output
Hardware	*Physical factors and capabilities of the human to perform during the interaction*	*Characteristics affecting the physical factors and capabilities of the human*	*Characteristics affecting the physical factors and capabilities of the human*	*Physical workload and workflow during interaction*	*Optimal HRI which is efficient.*
Software	*Cognitive factors and capabilities of the human to oversee the interaction*	*Characteristics affecting the cognitive factors and capabilities of the human*	*Characteristics affecting the cognitive factors and capabilities of the human*	*Cognitive workload and situational awareness of the human during interaction*	
Mindware	*The human experience and perception of the interaction*	*Characteristics affecting the human experience and perception of the interaction*	*Characteristics affecting the human experience and perception of the interaction*	*Perceived workload, job quality and complacency by human during interaction*	

bolster trust in the human worker before engaging in the next interaction with the robot. It is worth noting that, IMOI is a versatile model that not only allows a linear relationship between the different factors, but also assumes that, for example, mediator factors could affect each other.

The second facet, which sheds light on the problem form a different perspective, divides the safety factors based on their effect on the human worker's Hardware, Software and Mindware. These factors highlight the HF and OSH aspects. Looking at the input factors, hardware refers to the physical factors and capabilities associated with the human worker (e.g., PPE or health) or (technical) elements affecting this of the robot (e.g., lightweight or absence of sharp edges) and the environment (e.g., housekeeping). Software input factors are about the cognitive factors and situational awareness of the human worker (e.g., vigilance or experience) or elements affecting this of the robot (e.g., interface or complexity underlying algorithms) and the environment (e.g., time pressure or noise). Mindware input factors are about the experience and perception of the interaction by the human worker (e.g., trust or attitude) or the elements affecting this of the robot (e.g., appearance or consistency) and the environment (e.g., temperature or resource availability).

This adaptation of the IMOI model has, seven so-called mediators across the three elements:

- Two hardware mediators (Process and Physical workload);
- Two software mediators (Situational Awareness, Cognitive Workload) and;
- Three mindware mediators (Job Quality, Complacency and Perceived Workload).

These mediators ultimately affect the outcome of the interactions of humans with robots and the production outputs and facilitate the identification of risks in human-robot collaborations. For instance, if the human worker loses situational awareness, an incident becomes more probable and the interaction is not safe. Or: if the cognitive workload is too high, or the job quality is low, the interaction is not durable.

Summarizing, the IMOI model offers a systematic overview of concerns for safety and productivity in human-robot interactions. Its two facets, or viewpoints, are placed in a matrix to address each and every IMOI aspect on each element, as shown in Table 1. In this way, the model provides the basis for safety concerns and risk influencing factors for working with robots and cobots and shapes our holistic safety meta-model M1.

B. *M2 Safety measurement: profile wheel*

The IMOI approach casts a wide web in relation to risk-influencing factors but to make the model practical, a digital measurement method M2 was developed on top of a 360° diagnosis [10] product called 'profile wheel' 11]. The 360° diagnosis originates form health and lifestyle research towards a type 2 diabetes therapy. Similar to Human-Robot interaction, this therapy can only be established by a systems approach including all relevant (safety) factors of the matter to fit the individual situation [10]. In our case the factors in table 1 are mapped onto the profile wheel. A 360° diagnosis provides a large amount of data which makes interpretation difficult when remaining unorganized. Therefor the profile wheel exists to translate the 360° diagnosis into an effective and readable output and serve as a shared decision-making tool between patient and health care provider [11].

Our approach for the 360° diagnosis offers a digital questionnaire that is set against standardized performance levels to assess their performance. At the same time this offers insight into which influencing factors are performing better than others. The data enables to generate the profile wheel providing an instant overview of the current safety state of the human-robot interaction. Colors indicate the status of the main categories such that the end-user can easily identify the highest risks, as shown in Fig. 2. The profile wheel also allows to check the subcategories to figure which risk-influencing factors contribute most to the risk and what measures can be taken to increase safety.

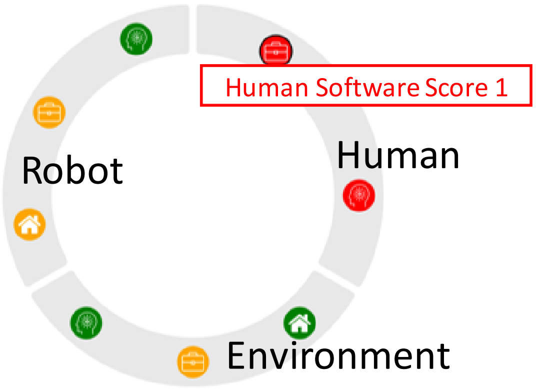

Figure 2: Illustration of the graphical output of safety measurement.

It is beyond the scope of this overview to describe the process for the development of the questionnaire in detail, but the first step is to select a subsection of IMOI elements that are relevant for safe human-robot interaction. Establishing this relevance could occur either through interviews or an automated check-in system based on certain questions, but a sizable chunk of the relevant aspects is similar in different environments. The second step is to identify safety elements that fit the description of an IMOI element; very often they are linked to safety controls that are part of existing safety models. It is not entirely coincidental that these controls also appear in the safety bowties (which are treated further on). Each element can now be populated with a number of questions that probe the status of the element. With sufficient questions on the subject a fairly straightforward scoring determines whether that safety element receives sufficient attention or that further investigation is warranted.

The 360° diagnosis and profile wheel function as safety measurement tool M2, and is founded on the safety meta-model M1. It is based on a questionnaire and visualizes safety issues insightfully in nine main categories that contain the IMOI risk influencing factors.

C. M3 Safety monitoring: bowties

With an indication of the safety situation, the next step is to monitor whether safety interventions and controls are delivering (M3). Here monitoring means quasi-real-time tracking of the integrity and proper use of the components safeguarding the system. This could include sensory data, (incident) reports, system configuration/maintenance updates or followed training modules by the employs. An effective way to deal with safety monitoring is with an established safety method: a bowtie. Bowties find their origin in chemical process industry and have been around for at least two decades [12]. It is beyond the scope of this conference paper to describe bowties comprehensively, but a high-level understanding of the main concepts is essential for understanding our work.

A bowtie is a safety tools that maps out the risk space surrounding a single unwanted event. Very often the unwanted event is an event that initiates an accident but it is easier to think of it as an event where your normal management processes are no longer in full control of a system. In terms of robot safety for a cobot that could be when part of the protective plating has come off or when the warning-lights are offline. The bowtie maps out all the observable and feasible ways in which that particular unwanted event arises, these are the so-called threats, and all the feasible adverse consequences. Together, these elements define the risk space surrounding that unwanted event. Within that space safety controls are installed and operated to prevent threats from propagating into an unwanted event or to prevent an unwanted even from propagating into adverse consequences (such as an injury). The controls are called 'barriers' and they are interventions that are installed and maintained by formal management processes within an organization.

Bowties can be used in different ways. They can be used in accident investigations to establish causal chains that were unknown, to establish whether barriers were missing or malfunctioning or how well recovery measures worked. Equally, bowties can be used to try and map out each and every possible risk scenario and each and every possible control barrier. In this work, however, the bowtie is used as a management control instrument that monitors organizational performance on safety for robots. For that, the approach described in the handbook for bowties by the CCPS [13]. This method was followed to the letter to design several effective and efficient bowties for robot safety, which could be named the fundamental bowties.

The GRIP tool uses these fundamental bowties to create a specific bowtie for an individual setup. This is done via a questionnaire which coincides for the greater part with the questionnaire used for the profile wheel. By indicating the state, likelihood or absence/presence of risk-influencing factors, the organization carves out the bits of the fundamental bowtie that they need for their local system.

As the bowtie model now encompasses the actual protective measures and interventions that the organization maintains as part of their safety management, the bowtie represents the risk space that the organization maintains in a graphical manner. From this point on, the bowtie becomes a systematic template to monitor the parts of that system. That means that if a barrier is taken-up in the bowtie, the technology components need to be in place, people need to be trained, procedures need to be followed, maintenance and audits need to be executed, and crucially evidence has to be gathered that the required tasks are performed adequately. This is where monitoring systems come in to play.

A chatbot was designed to monitor risk-events in the workplace. A chatbot was selected because it is relatively cost-effective and it helps employees report issues in their own words: they do not have to be gifted safety experts to share their safety concerns. The added value is in the direct (text)interpretation of the report which allows for interaction with the reporter which makes the reporting system easier to use whilst delivering higher report quality. The chatbot is trained to detect a number of relevant unwanted risks, electrocution is one and slip-trip-fall is another, but this can also be collisions with moving vehicles, missing parts etc. In this example the chatbot guesses that an electrocution risk is reported (which is not entirely impossible in this case), but the user perceives a different problem. Note that the user does not need to know all the risk scenarios; the chatbot supports the individual reporting (and leaves rooms for novel risks as well).

With many records collected an understanding can be developed about which threats or barriers are particularly troublesome (or working particularly well) which helps safety managers focus their attention. Notice that this digital monitoring solution offers efficient and effective safety monitoring as well as a structured method to collect data. This is one single digital solution for safety monitoring but many more are under investigation.

Summarizing, bowties can map the risk space of complex systems and show how to monitor the components safeguarding the system. Custom bowties are easily generated based the same questionnaires as used for the measurement system (M2) Which in turn were founded on the safety model (M1). A chatbot complements the monitoring tool (M3) for real time human centred recording of risk-events. This practical solution contributes to the final step in the development of a digitized robot safety management system based on the 3M approach.

III. LOOKING FORWARD FOR APPLICATIONS

GRIP has been used on two use cases in cooperation with two organizations that specialize in consultancy and risk analysis concerning robot applications. It was found that the safety measurement based on the IMOI model, the ease of collecting the relevant information and the instant visualization provided added value, but the form of the questions needed improvement; most notably changing yes/no questions to Likert scale questions (1-5), reducing the number of questions and altering the language somewhat. A specific boon was the digital setup which made it easier to perform a safety analysis regardless of location; despite that it was felt that the actual cobot had to be 'seen' to fully grasp all safety aspects. But even with that in mind, it was thought that less time would be needed for a thorough assessment. The use cases with industry partners did not yet include the development of a management system (M3). This module was uncompleted at the time but is scheduled for testing early 2021. With several use cases done, and planned for 2021, it is expected that two iterations with industry suffice to develop a system that is sufficiently developed for industry application.

An important piece of feedback is that, even if GRIP focused on HF and OSH concerns (so after certification and installation of a robot or cobot) it would be good to add safety questions relating to the machine directive [14]. Elements such as the availability of (spare) safety components and a manual for the machine were thought to be relevant to for training of staff which makes it an OSH concern. As the questionnaire is adapted after the first use cases, this will be taken aboard for the next iteration of GRIP.

Slightly on a tangent, the safety-chatbot has attracted attention as a stand-alone product. It seems that making it easier for staff to share their safety concerns in a supportive system has some benefit in its own right. However, more work is needed to assess a) operational limitations of chatbot technologies b) incorporation of effective safety learning c) the quality of the data generated and d) the effect on staff.

IV. CONCLUSION

A digitized solution approach for robot and cobot safety assessment, considering human factors and occupational safety and health, is beneficial for industry because it combines in-depth scientific understanding of safety with rapid implementation. In addition to that digitalization makes it possible to share data for different safety purposes. In this case they are a safety measurement (assessing the current situation) and a safety monitoring system (assuring that safety levels are maintained over a prolonged period of time).

This paper demonstrates that safety management for robot- and cobot safety cannot depend on a single safety tool. Therefore, we use the 3M approach in GRIP, model, measurement and monitoring. A combination of different tools and methods is required for safety management and any attempt to collapse different interests in a single digital tool is likely to make safety management more difficult rather than easier. With that understanding, depending on safety standards alone seems an unwise approach.

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