Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio

doi: 10.3850/978-981-18-8071-1_P405-cd

Adaptivity in human-robot-interaction

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The recent developments in the collaborative application of robotic systems introduce a close Human-Machine Interaction (HMI). Most efforts focus on defining safe scenarios during solution designs and standardization of processes, while cognitive and psychological aspects remain important factors to be further developed. New technologies increase productivity and flexibility, but new or higher risks can arise if not well managed. Industry 5.0 places the wellbeing of the worker at the centre of the production process.
The new regulation on machinery products requires that manufacturing-companies avoid all risks related to moving parts and psychological stress at the same time. In particular, it requires that machinery products with a certain level of autonomy, and fully or partially evolving behavior or logic, should be adapted to respond to people adequately and appropriately.
This means the interaction system shoud be designed to get proportionate to the required input and to the reaction or behaviour that has to be determined (for ex. requiring the attention, improving the situation awareness, maintaining a right level of stress), suitable for the intended context, scenario and task.
In this study, we analyse the issues for operator's safety and health in a robot system application and the opportunities to design adaptive systems.
This paper highlights those characteristics miss in technical standardization in order to be compliant with the new requirements of new Machine Regulation to maintain the right Mental Work Load (MWL).

Keywords: industry 5.0, human-centric, collaborative robot, adaptive systems, safety

1. Introduction

Industry 5.0 recognizes the power of industry to achieve social goals beyond jobs and growth to become a resilient provider of prosperity, by making manufacturing/industrial production respect the boundaries of our planet and placing the wellbeing of the worker at the center of the production process. The vision for Industry 5.0, unlike Industry 4.0, goes beyond efficiency and productivity and focuses on human progress and well-being of workers. Where 4.0 technologies help to improve manufacturing/industrial production considering needs and abilities of workers, Industry 5.0 requires technology adapting to the worker, never the opposite way. Smart technologies like IOT, robot, AI, AR are in all contexts of society and of work, in healthcare too, as well support and help normal activities and jobs. In this context, the robot improves a worker's health and wellbeing, for example, when it performs a risky task for him/her or when it goes into a risky environment.

There are different types of robots, including autonomous robots, teleoperated robots and collaborative robots.
In this study, we analyze the Human-Robot-Interaction (HRI) looking for useful indications to manage the risks of such interaction, especially focusing on the ergonomic requirements
Until now, ergonomic requirements mainly refer to physical ergonomic requirements, according to technical standards, which suggest measures to manage the related risks. In the future, work will be mostly human-robot co-working; this is already the case in many industries.
Automation can help humans in lightening heavy tasks, but a greater cognitive effort is required in order to manage and relate to robotic systems: less physical than cognitive effort.
Sustained attention is more important than physical endurance, and problem solving is more necessary than physical skills.
As a result, to improve safety at work, an adaptive cognitive system has to be embedded when man interacts with robot, especially in tasks that require a strong cognitive effort.

2. Cognitive Workload

When exposed to stimuli, the cognitive system experiences what is commonly referred to as cognitive effort.
Performing a specific task requires a Mental Work Load (MWL) for the human cognitive system; Cognitive Load Theory (CLT) considers three main aspects:

- *Input – mental load:* it refers to external events or factors that the operator cannot directly control (such as difficulty of task, environmental physical risks, types of display, layout of workplace, instructions)
- *Effort – mental effort:* it refers to either load or stress of operator. It depends on physiological characteristics of operator, background, personality, experience, motivation and attention of the operator
- *Performance*: it is the result of the work performed. If positive, it helps in learning new skills and improves human-machine interaction.

Input, Effort, and Performance constitute the three measurable dimensions of human cognitive system and then the MWL.
It is generally recognised that Performance degrades where the MWL assumes extreme values, either excessively low load (underload) or excessively high load (overload).
Low workload levels are associated with boredom and decreased attention to task, whereas high workload levels are associated with increased error rates and too narrowing attention.
Results of research activities suggest that reaching an optimal MWL leads to better information retention, less exhaustion and more working enjoyment.
The study of MWL starts from acquiring and processing human data from real situations (such as interacting with a robot system) and it will allow to modify and to improve the system that generated them.
The assessment and prediction of cognitive Performance is a key issue in order to improve risk prevention in the HRI, because it can help us to understand–the intrinsic limitations of the human information processing system. This can suggest to us measures to manage them with adaptive solution for design of interfaces, for communication systems (input and feedback), for task scheduling, etc.
Measures of MWL result either from the process of subjective self-assessment[a] or from objective psycho-physiological or neuro-physiological analysis.
Through the monitoring and interpreting of objective and subjective data during the interaction between a human operator /user and an industrial/service robot, it is possible to obtain information about the user's inner experience in terms of emotional and cognitive states.
Until now, researches developed theoretical frameworks for measuring MWL, but a standard that gives measures to calibrate a model of HRI (task demand, arousal, mental workload and human performance) so that the MWL is optimal (neither too high nor low) is still missing.
That is, the preferential MWL indicator for tasks performed by an operator in the shared workspace with a robot has not been identified.

[a] NASA-STD-3001 Technical Brief

Moreover, a universal metric system to measure the specific meaningful values still does not exist. The international standard on MWL (ISO 10075-3[b]) addresses procedural and quantitative requirements for instruments measuring different aspects of mental workload, in particular for stress, but it does not specify which instrument should be used. It gives requirements (criteria) for the objectivity, reliability and validity of measurements so that instruments used will fulfill the psychometric criteria.

It is necessary to develop research activities in close collaboration with industry, end user of developed technologies in order to fill the gaps and improve safety, health, comfort and long-term productivity too.

Robot systems can collect data from sensors embedded on the hardware, fixed in the environment and worn by humans (using wearable devices). These devices enable data analysis and development of better real-time control algorithms in order to improve safety and the health of operators as it has already been developed for position and movement monitoring of the human body.

Measurement of motion using wearable devices such as Inertial Measurement Units (IMUs) can improve the risk assessment related to the risk of contact with moving parts and collect data from the human behavior. Inail funded, with a call for bids in collaboration BRIC ID-12/2018 won by the Universities of Torino, Bologna and Cassino, a research project SIC-o-MAN (Safety Of Maintenance operator) in order to develop adaptive cinematic algorithm starting from detailed data of the operator's movement (see fig.1).

Fig.1 – call for bid Sic-o-Man

[b] Ergonomic principle related to mental workload – Part 3: principles and requirements concerning methods for measuring and assessing mental workload

3. Regulatory Landscape for a Safe Robot Interaction

Industrial (and service) robots fall within the scope of the Machinery Directive 2006/42/CE, still in force today, that requires developing a risk assessment in order to eliminate and reduce risks since designing of machines. It requires that "Under the intended conditions of use, the discomfort, fatigue and physical and psychological stress faced by the operator must be reduced to the minimum possible, taking into account ergonomic principles such as:

- allowing for the variability of the operator's physical dimensions, strength and stamina,
- providing enough space for movements of the parts of the operator's body,
- avoiding a machine-determined work rate,
- avoiding monitoring that requires lengthy concentration,
- adapting the man/machinery interface to the foreseeable characteristics of the operators".

The guide to the directive specifies that this list is not exhaustive, but only indicative. Considering the last principle, it already introduce the adaptive concept of the interface: it requires interfaces adapt to the characteristics (in general, limited to the physical ones) of the operators.

The standard EN ISO 12100:2010[c], a harmonized standard to the 2006/42/CE MD, requires that manufacturers' risk assessment shall define the use limits of the machine, including the intended use and the reasonably foreseeable misuse. Specifically, it highlights to include:

- the use of the machinery (for example, industrial, non-industrial and domestic) by persons identified by sex, age, dominant hand usage, or limiting physical abilities (visual or hearing impairment, size, strength, etc.);
- the anticipated levels of training, experience or ability of users

[c] EN ISO 12100 Safety of machinery - General principles for design - Risk assessment and risk reduction k assessment and risk reduction

including operators, maintenance personnel or technicians, trainees and apprentices, and the general public.

This standard highlights the necessity, inside the request of considering the reasonably foreseeable misuse, to know operator's behavior or better common misuses in order to prevent and avoid injures.

Among examples of unintended behavior of the operator or reasonably foreseeable misuse of the machine, it lists:

- behaviour resulting from lack of concentration or carelessness,
- behaviour resulting from pressures to keep the machine running in all circumstances.

Then this standard suggests considering the operators' behavior in the analysis of risks as one issue to address with risk assessment.

By now, changing the technological landscape, machines are becoming more powerful, autonomous and some look almost like humans. New Regulation on Machine Products proposal[d] receipts the need to update Essential Health and Safety Requirements (EHSRs) especially those related to the contact between the human and the machinery i.e. EHSRs 1.1.6 on ergonomics and 1.3.7 on risks related to moving parts and psychological stress.

New Regulation will require taking into account also "Adapting the human-machinery product interface to the foreseeable characteristics of the operators, including with respect to a machinery product with intended fully or partially evolving behaviour or logic that is designed to operate with varying levels of autonomy; considering the possibility of customization operated with AI systems*."*

This bullet extends the application of the previous one to the new machines, introducing the customization of the product interface to the (foreseeable) characteristics of the operator.

Characteristics of operators are not limited to physical ones, but they also contain cognitive and emotional ones. Both features influence interactive system such as collaborative robots, but the technical standardization (see paragraph 3.1) only considers physical characteristics in the measures suggested.

Moreover, the next bullet introduces a new ergonomic principle: "(f) adapting a machinery product with intended fully or partially evolving behaviour or logic that is designed to operate with varying levels of autonomy to respond to people adequately and appropriately (verbally through words and non-verbally through gestures, facial expressions or body movement) and to communicate its planned actions (what it is going to do and why) to operators in a comprehensible manner".

This EHSR highlights that the robot has to respond with people adequately and appropriately, then the response has to be proportionate to the required input and to the reaction or behavior that has to be determined (for ex. requiring the attention, improving the situation awareness, maintaining a right level of stress), suitable for the intended context, scenario and task.

It is possible fully achieving this objective only considering physical and physiological characteristics of workers performing specific tasks.

Then the machine product can be–responsive to human needs of information and communicate its planned action in a comprehensible manner. Main means of communication usually adopted in design of "traditional" machines are visual (messages conveyed by means of brightness, contrast, colour, shape, size or position such as signals on the Tool Center Point and/or on the chassis, using different colors and shapes, facial expression) and acoustic ones (messages conveyed by means of tone, frequency and intermittency, emanating from a sound source). Robots having a direct or a closer interaction with humans have an additional mean of communication: tactile ones.

Anyway, an effective communication will maintain the engagement of the operator when it needs, especially in hazardous scenarios.

It is necessary to know MWL of the operator during collaboration to maintain his/her engagement in a safe and healthy level. It is not enough to know the human-robot position or power and force limits for human being, but it is necessary to know cognitive and emotional features and limits of the operator.

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[d] Proposal for a Regulation of the European Parliament and of the Council on machinery products. Document date: 20/04/2021 - Created by GROW.01 - Publication date: n/a - Last update: 21/04/2021

The new regulation so introduces the need to consider MWL, focusing on *Effort* so that the system predicts the behaviors of the operator and on "Input-mental load" so that robot's design adapts to human information and communication needs.

3.1. *Industrial robot*

Technical standard for industrial robot system (EN ISO 10218-2:2011[e]) requires that the risk assessment shall consider the following features for ergonomics and human interface with equipment:

(i) visibility of operations;
(ii) clarity of controls;
(iii) clear association of controls with robot system;
(iv) regional control design traditions;
(v) position of work piece relative to the operator;
(vi) foreseeable misuse.

The standard mainly refers to the control interface, in order to avoid confusion, misuse etc. HRI can take place with the whole robot: its movements, its sensors, its shape, materials, colours and more, not only the control interface and device like "traditional" machines.
The end-effector and the load can be very different each other. It is possible to have robots for handling unit of loads, robots for welding, processing materials and so on. Every robot has its risks and different possible collaborative tasks. For example, the standard currently in force refers to force and pressure limit values beyond which human-robot contact cannot be acceptable. These values result from the study of Institute for Occupational, Social and Environmental Medicine at the Johannes Gutenberg University of Mainz, Germany "Collaborative robots – Investigation of pain sensibility at the Man-Machine-Interface". The maximum permissible pressure values shown represent the 75th percentile of the range of recorded values for a specific body area. This study can be developed for other anthropometric measures and extend the operator target, but it does not consider the movement of operator before and after the contact: it only considers static or transient contacts. During a collaborative application, contacts can occur voluntary (for ex. to move a link giving a command or stopping the machine) and not voluntary (for ex. reaction to a movement of the robot due to fatigue, stress).
Taking into consideration the right MWL it is possible preventing or reducing the likelihood of not voluntary behavior (reactions). To get robot system more productive, functional to human limits and then safer it is critical to know the cognitive and emotional states of operators.
In this regard, the new standard proposal (FDis) specifies, for power and force limited robot, the following "hazards specifically rising from:

- The design and location of any manually controlled robot guiding device (e.g. accessibility, ergonomic, potential misuse, possible confusion from control and status indicators, etc.);
- Deficiency in ergonomic design (e.g. resulting in loss of attention, improper operation)."

It attributes to design the cause of loss of attention.
The design must be functional to the right MWL, and it should be implemented not only for designing the control interface, but also for the whole robot system.

4. HRI Issue for Industrial Collaborative Robots

The risk assessment is particularly heavy for considering all possible situation of the HRI that continuously changes. A collaborative application is usually divided into subsequences having different HRI and risk scenarios. In this regard, changing of process parameters such as the change between autonomous operation of robot and manual/collaborative operation is a critical point for health and safety of operators, as highlighted by technical standards EN ISO 10218:2011 point "5.11.4. Change between autonomous operation and collaborative operation (…) is a particularly critical part of a collaborative application". In collaborative

[e] Robots and robotic devices — Safety requirements for industrial robots — Part 2: Robot systems and integration

application, humans and robots are close in a space, often executing many autonomous automatic and manual/collaborative tasks alternatively and/or simultaneously: the operator enters and exits from the collaborative workspace.

We highlight that the risk assessment defines the collaborative space but humans do not physically perceive its limits in space. All of that can affect the operator's performance and worsen the safety. This uncertainty can induce stress for the operator and affect MWL.
Moreover, the standard identifies four collaborative applications:

(i) Safety rated monitored stop (SMS)
(ii) Hand guiding (HG)
(iii) Speed and separation monitoring (SSM)
(iv) Power and force limiting (PFL)

Each of these define different possible interactions and then hazard scenarios.
In SMS collaborative application humans and robot do not work simultaneously: the robot shall stop when a human is in the collaborative workspace.
Conversely, it may resume automatic operation when human leaves that space.
HG collaborative application allows the operator to move the robot to the intended position, teaching the trajectory and the end-point. When the robot system reaches the hand-over position, a safety-rated monitored standstill is active.
SSM collaborative application does not allows the robot system getting closer to the operator(s) than the protective separation. Moreover safe separation distance between the operator and the robot system can be given in a dynamic manner.
It means that the robot knows the relative position and speed, keeping the safe distance (obviously, it can get closer with low speeds).
During PFL collaborative application physical contact between the robot system (including the work piece) and an operator can occur either intentionally or unintentionally. Risk reduction is achieved, either through inherently safe means in the robot or through a safety-related control system, by keeping hazards associated with the robot system below threshold limit values.
An industrial robot system can have all the safety features allowing different collaborative applications and scenario interactions.
Information about the collaborative application in use must be available and immediate, especially in case it changes from one to another during the execution of a task. These continuous changings are intrinsic in HR collaboration then its necessary to investigate how and when (adequately and appropriately) communicate to the operator the state of the robot, so that he/she will perform safely as required by a MWL-based design.

5. Conclusion

The Industry 5.0 complements and extends Industry 4.0 paradigm. It focused around three interconnected core values: human-centricity, sustainability and resilience. This means to put human needs and interests at the heart of the production process, so that to satisfy and ensure worker's physical health, mental health and wellbeing. Clearly, because many activities have been automated reducing human physical effort with Industry 4.0, it remains that the human centred approach must be focused to improve the design of the interaction human- machine in collaborative systems, where the communication systems are critical.
A human-centred design requires that technologies adapt themselves to the human needs and characteristics. In turn, the development of these technologies need to have data about the state of humans: field studies showed that mental and emotional state plays a fundamental role in the right execution of a task as well as in avoiding injuries.
This paper focuses on HR collaboration and safety requirements of related product directive and technical standards actually in force, or shortly coming. New regulation introduces requirements according to a human centred approach, but a standard with specific measures is still missing. It is necessary to develop indications about what and how data monitoring in order to predict the probability of performance impairment during operational scenarios (tasks) which may be safety-critical. As highlighted, change between autonomous operation of robot and manual/collaborative operation is a critical point for health and safety of operators and often human and robot execute many manual and autonomous tasks alternatively and/or simultaneously. Have a right MWL-based design

of the whole robotic system will avoid stress and will reduce errors and then risks for health and safety.
It is desirable that there will be new standards to guide the designer in risk analysis and assessment on cognitive ergonomics in order to manage the relationship between *Input* design and *Effort* to get a better performance in HRI.

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