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Balancing intended collaboration and safety requirements during the design and implementation of an industrial cobot application - A case study

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ABSTRACT

The aim of this article is to illustrate, through a real-life case study, the importance of balancing the intended human-robot interactions and occupational health and safety (OHS) requirements when designing and implementing a collaborative application involving industrial robots (in the sense of ISO 10218). This article discusses the obstacles and efforts involved in achieving greater but safe collaboration by chronologically detailing the risk reduction approach.

A consortium of manufacturers commissioned the National Research Council Canada (NRC) to implement a TRL-5 cyberphysical finishing cobotic platform for companies of the metal industry. By finishing, we mean polishing, grinding and deburring tasks on metal parts. While the cobot performs the finishing tasks, the human operator supervises the process, oversees the quality control of the parts and indicates which production lot should start. The main reasons behind the consortium's request were: 1) the need to alleviate the musculoskeletal disorders among the finishing operators, 2) the labor shortage and 3) a drive to innovation. The robotic platform consists mainly of a support table with a dust extraction system, a 6-axis cobot arm attached to a rail to add a 7th axis, accessories and tools for part finishing (e.g. compliance head, abrasive discs). The industrial robot used was a UR10 cobot.

One of the initial objectives was for the finishing platform to be collaborative to ensure flexibility and fluidity of operations. Typically, a needs analysis and a risk assessment help determine the feasibility and the usefulness of a collaborative application. However, in the case of the NRC's laboratory application, a different approach was taken. The pursuit of innovative solutions to increase flexibility in finishing activities required to push the limits of technology and to explore what is achievable and what is not. In fact, such an approach is frequently employed in the industrial context. Thus, an iterative risk assessment was carried out once the platform structure has been assembled. First, fifty-five risks have been identified, including mechanical risks coming from the cobot arm movements and the disc rotation. Regarding those mechanical risks, the protective measures the OHS team suggested allowing the operator to be close to the functioning cobot were 1) a reduced speed of the moving cobot arm to 16 mm/s (PL = d, category = 3), 2) a protective stop, of the moving arm, triggered by a PLe, cat. 3 Airskin "sensitive skin" in the event of contact, 3) PLe, cat. 4 emergency stop buttons and 4) a protective stop, of the rotating disk, triggered by two PLd, cat. 3 laser scanners in the event of intrusion into the safeguarded space. Personal protective equipment (PPE) has also been suggested. The residual risk was then considered acceptable only if the disc was at a standstill. However, the protective measures concerning the rotation of the disc conflicted with the collaborative application intended by the consortium and the expressed need to approach the rotating disc during finishing to perform a visual quality control of the part (operator positioned approximately 200 mm from the tool). As a result, the solution proposed by the OHS team at this new stage was to allow access to the zone using a dead man's switch (DMS) to bypass the scanners' protective stop, combined with wearing close-fitting clothing, tying back hair, and wearing PPE to protect against the risk of projections and gloves to protect against the risk of cutting with the disc. Wearing gloves was intended to reduce residual risks since contact with the disc remains possible (e.g. free hand, inertia of the disc to stop). To verify the actual hand protection provided by gloves, five models offering high mechanical resistance were tested with two abrasive discs in different configurations. The tests consisted of rotating the disc at 9,000 rpm (operating speed), bringing it close to the glove at a speed of 16 mm/s with the cobot arm, then touching the glove for a fraction of a second to simulate unexpected contact (withdrawal of the arm when the force sensor measures 70 N in contact with the support inserted into the glove). The results were unequivocal: all gloves were cut or torn. Thus, wearing gloves will not protect the operator in the event of contact with the rotating disc on the finishing platform.

In the end, the protective measures proposed when the disc is rotating (i.e. scanners + DMS + PPE) can be considered acceptable for setup or teaching as described in clause 6.2.11.9 of ISO 12100:2010. This is the case during the implementation of the platform. However, it will not be sufficient for industrial use. According to clause 5.5.5.3 of ISO/TS 15066:2016, "parts which could cause injury shall not be present in the contact area" with the robot. For the platform to be considered collaborative in production, with the intended human-robot interactions, research and development still needs to be carried out. Avenues to explore include 1) more precise monitoring of the area around the disc (e.g. sufficiently reliable vision system) coupled with a dedicated brake on the disc, 2) a disc protector adapted to the constraints of the process, 3) programming safe trajectories by following pre-established rules (e.g. order and direction of arm deployment, favouring trajectories of the disc when finishing towards the centre of the table rather than towards the outside) and 4) keep the operator out of the zone when the disc is rotating whenever it is possible by using other options (e.g. miniature camera fixed on the compliance head for inspection). In conclusion, this project illustrated how the intended level of collaboration and OHS risk management requirements must be considered together when designing and implementing such an application to deliver the desired level of flexibility. In this case, the potential OHS issues were highlighted early in the project, enabling the team to address it through innovation.

1 CONTEXT

1.1 Integration of a finishing cobotic application in NRC's laboratory

A consortium of manufacturers commissioned the National Research Council Canada (NRC) to implement a TRL-5 cyberphysical finishing cobotic platform for companies of the metal industry (TRL: Technology Readiness Level). By finishing, we mean polishing, grinding and deburring tasks on metal parts. The objective set is to develop a complete automation of the finishing process for complex metallic parts, going further than some previous work on the subject [1]. For example, the system must be able to process the part as it is fixed to the table without any specific preparation in terms of part orientation. While the cobot performs the finishing tasks, the human operator supervises the process, oversees the quality control of the parts and indicates which production lot should start. The main reasons behind automation and the consortium's request were: 1) the need to alleviate the musculoskeletal disorders among the finishing operators, 2) the labor shortage and 3) a drive to innovation.

At present, the robotic part of the platform consists mainly of a support table with deflectors and a dust extraction system, a 6-axis cobot arm attached to a rail to add a 7th axis and specific tools for part finishing (Figure 1). The industrial robot used is a UR10 cobot mounted upside down on a linear range extender. This configuration expands the robot workspace and reduces the number of setups required to finish parts. To ensure adaptation to the workpiece geometry variations and application of a prescribed finishing force on the workpiece surface, compliance heads have been added to the robot. Grinding discs are attached to the compliance head. The developed platform also includes a 3D scanning system for part digitization and scene cameras for gesture recognition, enabling operators to interactively assign tools and process parameters to selected surfaces/curves and modify them during task execution if necessary. Thus, the objective of an interactive collaborative platform has been set and innovation covers several aspects including 3D model reconstruction, interactivity via touchscreen and gesture recognition as well as robot motion optimization.

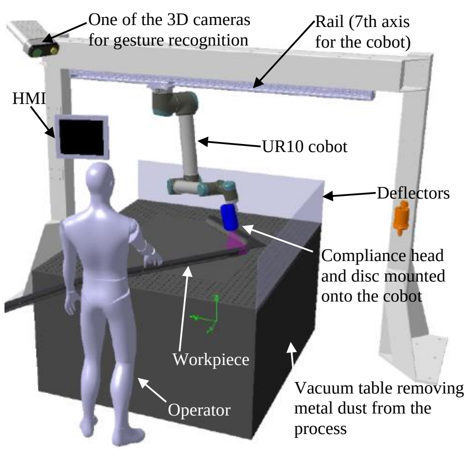

Figure 1. *Sketch of the cobotic finishing platform (left) and the actual platform (right)*

1.2 Safety considerations during design

One of the initial objectives of the consortium was for the finishing platform to be collaborative to ensure flexibility and fluidity of operations. More specifically, the consortium's intent is to perform quality control on the part and adjustments with gesture-based controls, while minimizing production stoppages and guards around the application. As a reminder, a collaborative application is a process comprising at least one part of the industrial robot sequence where the robot, its robotic tool, the part being handled or worked on, the equipment or obstacles influencing the risks in use, and the operator are in the same protected space [2]. Based on the work of [3] on classes of collaborative application, this finishing platform application can *a priori* be classified as "occasional workspace sharing without collaboration" in which "the human and the robot perform different tasks for which they may have to share their workspace on an ad hoc basis. The human and the robot may also manipulate the same objects for different reasons in the workspace they share". The variables used by [3] to establish the classes include whether the task is executed by the robot and the human, sequence of operations, synchronization of operations, duration of the interaction, workspace sharing or not, distance between the human and the robot, gesture synchronization, pace control, etc.

Essentially, the proximity of the worker to the cobot in production increases the risk of injury. It is essential to prevent any collision, or to minimize its effect should one occur [4]. If the risk reduction measures are inadequate, damage will be caused by the cobot, its tool (e.g. gripper, disc), the part being handled or worked on, or the immediate environment with its obstacles or auxiliary equipment. Based on the needs expressed by the consortium and the four safety methods allowing collaborative operations according to [5], the *a priori* method considered here are "speed and separation monitoring" (the robot moves avoiding the moving human and tries to keep a protective separation distance between them, if that distance is violated, the robot stops) and "power and force limiting" (can be achieved by inherent design (e.g. padded joints) or control by configuring the appropriate threshold for the force limit).

Safety can be a barrier to adopting cobotics [6]. The barrier could be explained by a lack of comprehension regarding safety in general and, more specifically, safety standards and risk assessment [7,8]. Typically, a needs analysis and a risk assessment help determine the feasibility and the usefulness of a collaborative application. The integrator must anticipate from the start of the integration process, several aspects of which will have an impact on safety [3]. In this case, as the pursuit of innovative solutions required to explore what is achievable for the finishing technology, an iterative risk assessment was carried out once the platform structure has been assembled and not the other way around. In fact, such an approach is frequently employed in the industrial context. Even if OHS was not considered at the very beginning of the design process, its inclusion during development (and not at the end) is a step in the right direction. As one of the NRC's research partners, the IRSST oversaw the occupational health and safety (OHS) aspects of the platform.

2 OBJECTIVE AND METHODOLOGICAL ASPECTS

The IRSST's team mandate was to analyze the risks associated with the finishing application, and to support risk reduction while keeping in mind the intent of a collaborative platform. However, the aim of this article is rather to illustrate, through a real-life case study, the importance of balancing the intended human-robot interactions and occupational health and safety (OHS) requirements when designing and implementing a collaborative application involving industrial robots (in the sense of ISO 10218). Conflicts sometimes appear between what the client wants in terms of collaboration and what is possible according to safety standards, because of the risks involved. This article discusses the obstacles and efforts involved in achieving greater but safe collaboration, as defined in ISO 10218-1:2011 [9], by chronologically detailing the risk reduction approach related to the rotating disk. This is a continuing endeavour throughout the technological evolution of the application until the TRL-5 platform is ready for a transfer to the metal industry.

As recommended by [5, 10], a risk assessment was carried out including defining the limits of the application, identifying hazards, estimating and then evaluating the risk associated with the hazardous situations identified. The limits of the application were determined according to the variability factors set out in [3], a parallel study by the team on integrators of collaborative applications. The main variability factors include the following items: "characteristics of the robot–end-effector system", "safety options available initially" "characteristics of robot task", "handled workpiece", "characteristics of the human(s) involved", "characteristics of human task" and "characteristics and function of auxiliary equipment". For the risk estimation, the team used the tool available in the current confidential draft of ISO 10218-2 [2]. The team chose this 5-level risk estimation tool over the ISO 13849-1:2015 estimation tool [11] because it comprises more than two levels of severity of harm. That difference makes the next ISO 10218-2 tool less biased than ISO 13849-1:2015, considering the construction rules set out in an IRSST report [12]. The estimation was iterated three times: without any risk reduction measures, with the measures already in place, and with the proposed risk reduction measures. Risk reduction was carried out with the NRC team for risks greater than or equal to 3/5. The team also consulted finishing experts from two plants in the consortium. The experts demonstrated some finishing processes so the team could have a better sense of the hazards in the workplace. Finally, several tests related to risk reduction were carried out (e.g. resistance of gloves to cutting; scanners).

3 RISK ASSESSMENT AND REDUCTION FOR THE PLATFORM

The risk assessment of the platform involved 55 distinct risks generated by six kinds of hazards: 1) mechanical risks coming from the cobot arm, compliance head, rotating disc and workpiece; 2) chemical risks originating from the metallic particles and fumes in the finishing process; 3) thermal risks stemming from the explosive metallic dust, and the hot workpiece right after the finishing process (a vacuum table helped manage the chemical and thermal risks); finally, 4) electrical risk, 5) pneumatic risk and 6) noise arisen from the functioning of the platform.

The main mechanical risks related to the cobot arm movements (including compliance head) and the disc rotation are presented in Table 1. Regarding those mechanical risks, the protective measures the OHS team suggested allowing the operator to be close to the functioning cobot were a) a reduced speed of the moving cobot arm to 16 mm/s (safety parameter) (performance level (PL) = d, category (cat.) = 3 according to [11]), b) a protective stop, of the moving arm, triggered by a PLe, cat. 3 Airskin “sensitive skin” in the event of contact, c) PLe, cat. 4 emergency stop buttons, d) a protective stop of the rotating disk triggered by two PLd, cat. 3 laser scanners in the event of intrusion into the safeguarded space and e) a pneumatic locking system (PL = e, cat. 4) for the risk of compliance head ejection. The installation of two laser scanners under the table in compliance with [13] enables access control. Personal protective equipment (PPE) such as safety glasses, safety visor, protective gloves, safety shoes and smock and safety procedures have also been suggested related to the risks of ejection, falling objects and handling of parts [14].

Table 1. *Summary of the analysis of the main mechanical risks related to the finishing platform*

Hazard (grouping)	Hazardous situations	Possible harm	Risk index*	Risk reduction measures installed or commissioned	Residual risk
Moving cobot including compliance head and disc at a standstill	Body part in the path of … Body part between…	Contusion, abrasion, crushing, entrapment, shearing, fracture	4	**1)** Reduced speed of 16 mm/s (PL = d, cat. 3). Configured as safety parameter. **2)** Protective stop triggered by an *Airskin* sensitive skin (PL = e, cat. 3) in case of contact. **3)** Emergency stop triggered by an E-Stop button (PL = e, cat. 4). **4)** Training. Awareness to moving parts.	≤ 2
Rotating disc mounted onto the moving or stationary cobot	Body part in the path of the disc or between the disc and the table	Abrasion, irritation, cuts, sectioning, entanglement	5	**1), 3), 4)** **5)** <u>Protective stop triggered by 2 scanners if the operator comes too close to the disc (PL = d, cat. 3).</u> **6)** Flashing light. **7)** Safety glasses and visor, protective gloves, smock, tie hair back (e.g. residual risk posed by the inertia of the rotating disc).	≤ 2
Ejected or bursted rotating disc	Body part in the trajectory of the ejection	Cut, penetration, fracture, blindness	5	**1), 4), 5) 7)** **8)** Check disc before use. **9)** Check installation of disc shaft in chuck. **11)** Rotation speed limited to a minimum, while respecting production constraints and disc specifications. **10)** Move away when starting the cycle.	≤ 2
Ejected compliance head	Body part in the trajectory of the ejection	Contusion, concussion, fracture	4	**1), 4), 5)** **11)** Pneumatic locking system (PL = e, cat. 4). **12)** Appropriate safety shoes.	≤ 2

*Considering the application without its initial risk reduction measures

With the goal of reducing the level of residual risk to an acceptable level, disc rotation is not permitted when an operator enters the danger zone (active laser scanners), unlike cobot arm movements which are considered safe thanks to the risk reduction measures in place (reduced speed and *Airskin*). However, this protective measure concerning the rotation of the disc conflicted with the collaborative application intended by the consortium and especially the expressed need to approach the rotating disc during finishing to perform a visual quality control of the part. As a result, the solution proposed by the OHS team was to allow access to the zone, only to authorized personnel, using a dead man's switch (DMS) to bypass the scanners' protective stop, combined with wearing close-fitting clothing, tying back hair, and wearing PPE to protect against the risk of projections and gloves to protect against the risk of cutting with the disc. This measure for authorized personnel is related to the clause 6.2.11.9 of standard ISO 12100 [10]. However, the reduced speed condition for the rotating disc is not possible in this application due to the constraints of the finishing process, nor is there a dedicated brake on the disc. In this context, wearing gloves was considered to reduce residual risks since contact with the disc rotating at high speed remains possible (e.g. free hand and a bad reflex; inertia of the disc to stop; bypassing the normal use of the DMS). To verify the actual hand protection provided by gloves, five models offering high cut and abrasion resistance according to [15] were tested with two abrasive discs (including the most abrasive used) in different setups. A variety of materials (knitted and coated) were also targeted. The tests consisted of rotating the disc at 9,000 rpm (operating speed for the compliance head used), bringing it close to the glove at a speed of 16 mm/s with the cobot arm, then touching the glove for a fraction of a second to simulate unexpected contact (withdrawal of the arm when the force sensor measures 70 N in contact with the support inserted into the glove). All tests were repeated twice for each side of the gloves. The results were unequivocal: all gloves were cut or torn (Figure 2). Thus, wearing gloves will not protect the operator in the event of contact with the rotating disc on the finishing platform. This residual risk remains unacceptable. It was therefore proposed that activation of the DMS would not totally neutralize the laser scanners, and that a surveillance zone would be maintained, preventing anyone from approaching within 50 cm of the cobot's reachable volume. This 50 cm distance, when using the DMS, is a compromise in a research context to compensate for the fact that the speed of the disc is not reduced as prescribed. It is not a safety distance in the sense of [13], but a clearance distance in the sense of [16] to allow humans to escape. A manual restart procedure outside the zone is mandatory in the event of a protective stop [10]. The 50 cm is also a suitable distance to allow research personnel performing quality control.

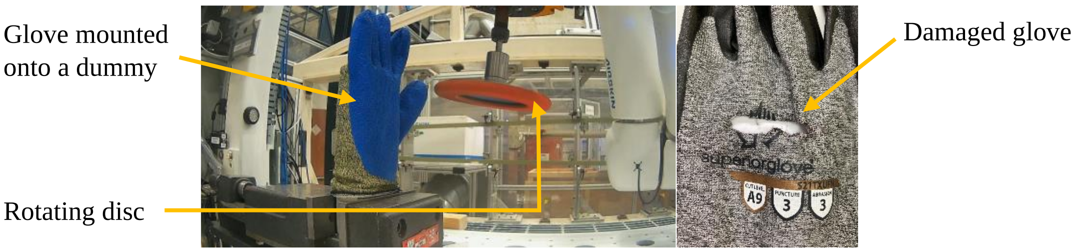

Figure 2. *Abrasion and cut testing of gloves with the disc (left) and example of a glove damaged during testing*

4 DISCUSSION AND CONCLUSION

According to the conclusions of [3] on the integration of collaborative robotic applications, the part to be handled and the type of robotic tool, among other factors to be taken into consideration, can have a major impact on risk reduction measures, including the use of external safety devices and even the collaborative vocation of the application, in the sense that the cobot is not at a standstill when a person approaches. This is the case with the finishing tool in the application studied in this paper.

In the end, the protective measures proposed when the disc is rotating (i.e. scanners + DMS + 50 cm distance + PPE) can be considered acceptable for setup or teaching in a research context [10]. However, it will not be sufficient for industrial use. According to clause 5.5.5.3 of [5], "parts which could cause injury shall not be present in the contact area" with the robot. For the platform to be considered collaborative in production, with the intended human-robot interactions, research and development still needs to be carried out. Avenues to explore include 1) more precise monitoring of the area around the disc (e.g. sufficiently reliable vision system) coupled with a dedicated brake on the disc, 2) a disc protector adapted to the constraints of the process, 3) programming safe trajectories by following pre-established rules (e.g. order and direction of arm deployment, favouring trajectories of the disc when finishing towards the centre of the table rather than towards the outside) or 4) keep the operator out of the zone when the disc is rotating whenever it is possible by using other options (e.g. miniature camera fixed on the compliance head).

In conclusion, this project illustrated how the intended level of collaboration and OHS-related risk management requirements must be considered together when designing and implementing such an application to deliver the desired level of flexibility. It is important that the integrator of the cobotic application conducts a first evaluation of the compatibility of the production constraints with safety requirements at the early stage of the process [3]. This analysis is part of a process involving the reduction of risk at source [10]. In this case, the potential OHS issues were highlighted early in the project, enabling the team to address it through innovation.

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6 REFERENCES

1. Kabir. A. M. *et al.* (2018). *Robotic Finishing of Interior Regions of Geometrically Complex Parts* [Communication]. ASME 13th International manufacturing science and engineering conference, College Station, Texas, USA. https://doi.org/10.1115/MSEC2018-6624
2. International organization for Standardization. (2023*). Robotics – Safety Requirements for Robot Systems in an Industrial Environment – Part 2: Robot Systems, Robot Applications and Robot Cells Integration*. ISO 10218-2 draft.
3. Jocelyn, S., Ledoux, É., Armas Marrero, I., Burlet-Vienney, D., Chinniah, Y., Bonev, I. A., Ben Mosbah, A. and Berger, I. (2023). Classification of collaborative applications and key variability factors to support the first step of risk assessment when integrating cobots. *Safety Science, 166*. https://doi.org/10.1016/j.ssci.2023.106219
4. Malm, T., Viitaniemi, J., Latokartano, J., Lind, S, Venho-Ahonen, O. and Schabel, J. (2010). Safety of interactive robotics—Learning from accidents. *International Journal of Social Robotics*, *2*, 221-227. https://doi.org/10.1007/s12369-010-0057-8
5. International organization for Standardization. (2016). *Robots and Robotic Devices – Collaborative Robots.* ISO/TS 15066.
6. Hentout, A., Aouache, M., Maoudj, A. and Akli, I. (2019). Human–robot interaction in industrial collaborative robotics: a literature review of the decade 2008–2017. *Advanced Robotics*, *33* (15–16), 764-799. https://doi.org/10.1080/01691864.2019.1636714
7. Aaltonen, I. and Salmi, T. (2019). Experiences and expectations of collaborative robots in industry and academia: barriers and development needs. *Procedia Manufacturing*, *38*, 1151-1158. https://doi.org/10.1016/j.promfg.2020.01.204
8. Berx, N., Decré, W. and Pintelon, L. (2022). Examining the role of safety in the low adoption rate of collaborative robots. *Procedia CIRP*, *106*, 51-57. https://doi.org/10.1016/j.procir.2022.02.154
9. International organization for Standardization. (2011*). Robots and robotic devices – Safety requirements for industrial robots – Part 1: Robots*. ISO 10218-1.
10. International organization for Standardization. (2010). *Safety of Machinery – General Principles for Design – Risk Assessment and Risk Reduction*. ISO 12100.
11. International organization for Standardization. (2015). *Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design.* ISO 13849-1.
12. Gauthier, F., Chinniah, Y., Burlet-Vienney, D., Aucourt, B. and Larouche, S. (2018). Risk assessment in safety of machinery: impact of construction flaws in risk estimation parameters. *Safety science, 109*, 421-433. https://doi.org/10.1016/j.ssci.2018.06.024
13. International organization for Standardization. (2010). *Safety of machinery – Positioning of safeguards with respect to the approach speeds of parts of the human body*. ISO 13855.
14. Jocelyn, S., Burlet-Vienney, D., Haj Zargarbashi, S.H., Gauvin, C., Galy, B. and Law. C.H. (2023). *Revealing the importance of estimating required reliability levels in cobotics safety* [Communication]. CIGI Qualita MOSIM 2023, Trois-Rivières, Canada.
15. American national standards institute & International safety equipment association. (2016). *American national standard for hand protection selection*. ANSI/ISEA 105.
16. Canadian standards association. (2014). *Industrial robots and robot systems - General safety requirements*. CSA Z434.