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Are collaborative robots safe?

Abstract: Collaborative robots (cobots) market is supposed to increase rapidly. Although cobots are safer than their ancestors, industrial robots, there are some safety issues. The risk assessment for cobots is difficult since the cobots are working beside humans. In most of the applications the cobots can be safe. Sharp tools or objects and risk of impact to head are excluded from the common applications due to their risks. The common idea is to apply power and force limitation to ensure safe performance of cobots. The speed of the robot has huge effect on the impact force. Speed reduction with adequate safety controls can decrease the impact force to acceptable level in most of the applications. If there are severe risks in the robot cell, then it is possible to apply adequate separation distance between human and robot or safety-rated monitored stop to ensure safety and relatively close vicinity between human and the robot. One issue is that the stopping performance is complex and currently it is difficult to predict. Quite often, the validation requires impact force/pressure measurements or impact modelling.

Keywords: functional safety, collaborative robots, safety requirements, levels of collaboration

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1 Introduction

Collaborative robots (cobots) have been under discussion for some years. They have some properties, which make it possible to work safely beside the robot. They are expected to open up new possibilities for flexibility, productivity and user friendliness. Also fenceless production cells are often mentioned.

Currently the world market of cobots is about 600 million € and at 2027 the market is supposed to be 7500 million € [1]. Collaborative robots are typically small and their reach is usually below 1.3 m and due to the size, their applications are often related to handling of small size objects. However, new applications are expected to appear.

The industrial robots are typically stronger, faster and more accurate than collaborative robots, but also cobots have some advantages. According to Kildal et al., the expectations of cobots are often fulfilled and in many cases, they are easier to program [2]. According to Bender et al., increased operational efficiency is the most frequent reason to choose a cobot. However, the payback time requirement for cobots is longer than for industrial robots. Very often cobots are evaluated by applying other than monetary terms. The most important values have been related to ergonomics, quality and flexibility. [3]

One advantage of the collaborative robots is that, usually, they are easier to program and the robot workspace does not have as many objects as the workspace of an industrial robot. On the other hand, collaborative robots are used in applications, which change more often than industrial robot applications. Continuous changes make it challenging to maintain adequate level of safety.

Although cobots are safer to use than industrial robots, according to Kildal et al. common opinion is that risk analysis is more difficult to make for cobots [2]. It can be understandable, since cobots are used in applications where human and robot are close to each other and it makes the risk assessment more difficult.

One special difficulty is related to force limiting of cobots, since the validation of force limits is difficult and the impact effect depend on the situation and how a person feels an impact. According to measurements at VTT a change of a parameter, especially, speed has an effect on impact force. Also Kirchner et al. points out that a parameter change of the robot cause unpredictable impact forces for many collaborative robots. Measurements can reveal the impact forces [4]. The aspect how a person feels an impact is difficult since Machinery Directive (2006/42/EC) is partly dedicated to enable trade by declaring uniform safety requirements. From the trade point of view, there should be applicable safety limits. The aspect how a person feels an impact is related more to user organization and related requirements (Work

Equipment Directive 2009/104/EC).

This text aims to point out factors, which need to be considered to estimate the safety of a collaborative robot. Many safety features have conditions, when their performance is adequate according to safety standards. Section 2 describes the collaboration of human and the robot. Section 3 points out safety requirements, which are important for cobots. Section 4 points out safety issues and measures, which are important for cobots. Section 5 presents safety design process model for collaborative robots. The process model is focusing on impact hazards and related safety measures. The idea of the process model is to point out factors, which have remarkable effect on safety measures to be used. Section 6 shows remarks related to safety of cobots.

2 Collaboration

Collaboration between human and robot can be realized in many ways and the separation distance, collaborative workplace locations and applied forces can vary from one application to another. The safety of collaboration can be based on inherently safe structures, guards, sensors, motion control, safe procedures and functional safety.

The ISO 10218-2 standard presents conceptual applications of collaborative robots, which are [5]:

- Hand-over window. Autonomous operation, reduced speed near the window, fixed or sensitive guards
- Interface window. Autonomous operation, except at the interface window the robot stops, fixed or sensitive guards, hold-to-run control.
- Collaborative workspace. Autonomous operation, person detection system, reduced speed according to distance.
- Inspection. Autonomous operation, person detection system or enabling device, reduced speed according to distance
- Hand-guided robot. Moving by hand guiding, hold-to-run control, reduced speed according to distance.

The above list does not show applications, which applies power and force limitation as a safety measure. Force limitation could be applied at any of the mentioned conceptual application and the collaborative workspace could allow more intensive collaboration.

Aaltonen et al. present four levels of collaboration. Here are presented the levels and comments how separation and speed control, like the dynamic safety system can be related to the level. [6]

- No coexistence: physical separation.
- Coexistence: human works in (partially or completely) shared space with the robot with no shared goals.
- Cooperation: human and robot work towards a shared goal in (partially or completely) shared space.
- Collaboration: human and robot work simultaneously on a shared object in shared space. Physical contact is allowed, possibility for hand-guiding.

The level of safety depends on the level of collaboration, due to the exposure time and separation distance. If there is no coexistence, the risk for a person is not so high since the person is not exposed to danger. It is more difficult to say the difference of the risk between the three other collaboration levels, although collaboration seems more risky due to obvious vicinity of the robot.

3 Safety requirements

Most of the collaborative robots are designed according to inherently safe principles. The collaborative robots are designed so that they should not exceed the defined force, at least with slow speed. In old robot safety standard (ISO 10218-1:2006) there has been a general force limit (150 N), but now the limit is specific for each body part of the human according to ISO TS 15066 [6]. The power and force limiting, brings new kind of thinking, since the contact is now a designed feature and not just a rare mishap. The designer needs to estimate, which body parts can be exposed to an impact of the robot and then limit forces accordingly.

The collaborative operations apply at least one of the means: safety-rated monitored stop, hand-guiding, speed and separation monitoring or power and force limiting by inherent design or control. The means are described more at the section 4.

One issue is that according to ISO 10218-2 section 5.2.2 safety related parts of the robots must comply with PL d and Cat 3 requirements of ISO 13849-1 [7]. This is related, among others, to stop, speed, area, power and force control. Many of the current robots do not comply with the requirements and therefore one have to consider, can e.g. a speed limit be applied to guarantee safety.

The ISO 13849-1 standard is related to functional safety of safety functions and associated control systems. The requirement levels are associated Performance Levels (PL) from “a” to “e” (highest level). There are both qualitative requirements, for example associated to software, and quantitative requirement i.e. the average probability of dangerous failure per hour. For PL d the probability value have to be below 10^{-6}. The factures, which affect the calculation of average probability of dangerous failure per hour (PFH_D) are: Mean Time to Dangerous Failure ($MTTF_D$), designated architecture (Category) and Diagnostic Coverage (DC). In addition, Common Cause Failures (CCF) are considered, but only to fulfil adequate requirements, not to for calculation. The category 3 is associated to duplicated structure (two channel system, one-out-of-two, 1oo2, hardware fault tolerance = 1), which is able to reveal single dangerous failures, since the duplicating part can perform the safety function, if one channel fails. The category 2 has also redundancy, but instead of duplication, diagnostics and alarms are applied to ensure safety. The two-channel system or failsafe (single fault safe) structure is considered more reliable than one-channel system with diagnostic, although the probability of dangerous failure per hour can be the same. The reason is that when applying two-channel system, the input data is not so sensitive to mistakes i.e. PL d can be achieved with lower $MTTF_D$ and DC values.

Fig. 1 shows safety measures and related standards according to ISO 10218-2. The basic design is made according to ISO 12100 [10] and then guards, safety distances and protective devices are selected and designed according to the relevant requirements.

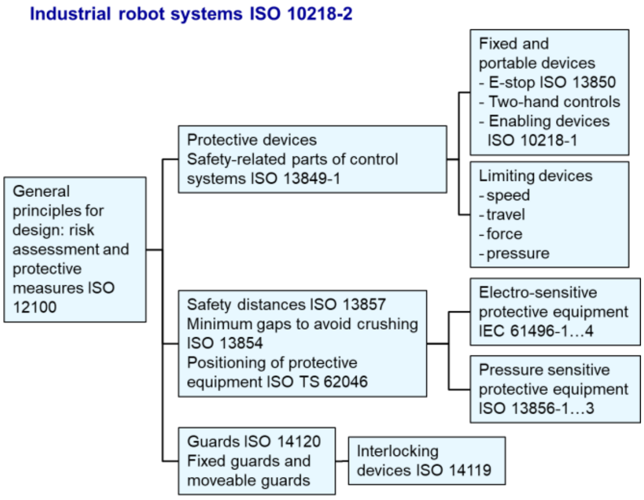

Fig. 1. Safety measures and standards of ISO 10218-2.

4 Safety issues and measures

Collaborative robots can be safer than heavy industrial robots. However, the collaborative robots are used in applications, where human and robot are close to each other and there is a high probability of impact. The intention is that human and robot work together. If the robot has sharp or dangerous tools, then similar safety measures as applied in industrial robot cells, are required. The ISO 10218-1 [9] describe the safety measures to collaborative robots from which at least one measure must be chosen. The measures are: safety-rated monitored stop, hand-guiding, speed and separation monitoring and power and force limiting by inherent design or control.

4.1 Safety-rated monitored stop

The stopping of the robot is monitored continuously and unauthorized movement case protective stop, which cut the power from servomotors. Protective stop resembles emergency stop (which is initialized by a person) and it provides, typically, safe stopping performance, but restarting requires manual start-up. Safety-rated monitored stop does not require manual restart, if the start-up can be made safely and persons at the restricted area are detected. Some robots have requirements fulfilling internal monitoring system, but monitoring can be done also by applying external monitoring system.

4.2 Hand-guiding

The robot is operated by applying controls near the end-effector. The controls include also emergency stop and enabling device. The robot applies safety-rated monitored speed.

4.3 Speed and separation monitoring

The position of the robot and humans are measured and speed is controlled according to the separation distance. The separation distance is calculated according to ISO 13855 (or ISO TS 62046), takes into account: stopping time of the robot, delays related to detection, communication and action, human speed, human reach towards danger point and uncertainty related to accuracy [11]. The speed can be reduced down to zero to avoid impact hazard. The robot should have safety-rated monitored speed function in order to realize flexible solution. Without safety-rated monitored speed reduction the separation distance would be long, i.e. often over 3 m, depending on the stopping time.

4.4 Power and force limiting by inherent design or control

Some collaborative robots have power and force limiting, which is based on either lightweight construction and/or quick, requirements fulfilling impact detection and stopping. If the load is heavy, also speed reduction is needed to fulfil the allowed max.

force/pressure limits. The force limits of the robot are difficult to realize accurately, since so many factors affect the result (e.g. speed, axis, horizontal/vertical movement, load). Due to complexity of the robot stopping performance, measurements are currently the only way to verify the achieved force limits related to quasi-static impacts (clamping) [4]. Transient impact forces (open space) are difficult to measure and therefore the forces are verified by applying calculation model. An example model is presented at ISO TS 15066. In the model an average hand is applied and for smaller hand, transient force would be smaller than the model value, since due to smaller mass the impact is more flexible (recoil).

In addition to the impact force limit values, there are also pressure limit values. Pressure values are difficult to measure and model, since it is difficult to estimate the effective impact area of the robot and the human. The impact area 1 cm^2 gives roughly similar speed limit values as force limit calculations. Smaller impact area (sharp edge) can give very high pressure values and therefore very small speed limit values.

4.5 Speed effect on impact force

Speed reduction reduce effectively the impact forces caused by the robot. Fig. 2 shows how speed affect the impact force in transient fully inelastic collision to hand and chest according to calculation model. Fig. 2 shows also that an impact with similar force is achieved for hand with higher speed than for chest. This means that when fulfilling the force limit requirements an impact to hand may be done with higher speed than for chest. One may conclude also that higher speeds can be applied if an impact only to hands is relevant. The robot weight in the model is 100 kg (heavy robot) and load 10 kg. Calculation is made by applying energy-based calculation model of ISO TS 15066 (equation A.5). In reality, some energy turns to heat and therefore the model gives a slightly pessimistic value. On the other hand, inelastic impact gives lower values than elastic impact, but partly elastic impact would be hard to calculate or compare to real impacts. The impact to hand is more flexible (reduced mass is small in the model) than to chest and therefore the force values for chest are higher at the same speed. For both hand and chest, the allowed limit force is 280 N (transient contact). The heavy 100 kg robot is chosen because the values are almost the same for heavier robots and therefore it represents a worst-case scenario. For smaller robots, the mass and load affect the model results strongly. Fig. 3 shows that the robot speed 2.6 m/s or below cause acceptable impact force to the hand. For smaller robots, the speed value is a little bit higher. The maximum speed of cobots (tool centre point) is usually close to 1.5 m/s, depending on the applied tool. If the impact is to the chest then the speed need to be below 0.7 m/s. To fulfil the impact force requirements, reduced speed is required if a person is working so close to the robot that it could hit the human body.

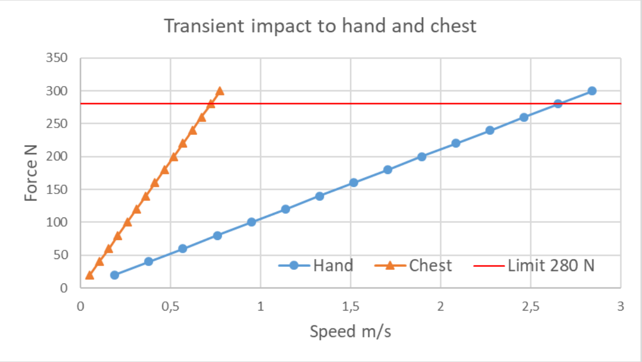

Fig. 2. Figure shows how similar transient impact force is achieved with higher speed for hand than for chest.

4.6 Other safety measures and issues

In addition, the mentioned obligatory measures, it is possible to use external tactile sensors or soft pads to meet the force limit requirements.

One safety issue related to collaborative robots is that they are applied in applications, which change often. This means that also risk assessment should be made often and it may be difficult to find new risks, if only quick risk assessment is done.

One aspect to be considered is that the robots may have exceptions to fulfil requirements. The robot system designer must check from the manual the conditions, when the robot can fulfil safety requirements. Following aspects are examples of conditions stated by manufacturer of the cobot:

- some conditions may hinder detecting impacts (e.g. specific positions, slow speed),
- there can be stopping performance parameters (e.g. stopping category and performance level)
- high speed or force limits may cause different safety requirements (e.g. overriding),
- control of singularity points may require additional tasks to maintain safety and
- acceleration/deceleration parameters affect stopping performance (slower deceleration can increase impact force).

One obvious issue is the applied tools. A sharp tool is usually dangerous and the robot work area may have corners or other machines, which cause potential hazard if human body part is clamped against it. In addition, grippers may be hazardous, but there are also models, which take into account the human presence.

5 Safe design process model for collaborative robots

Safety design process for collaborative robots (Fig. 4) is part of machinery safety design process (see Fig. 3). According to the design process, first risk assessment is applied to find out, which parts of the machine need safety measures. Basically, risk assessment is required to identify risks. Risk identification is made by applying, usually, hazard list of ISO 10218-2. The next phase risk estimation can be made according to harmonized standard, if the risk is described there. If the risk differs from the harmonized standard, then risk estimation and evaluation need to be done and documented carefully. Support to risk evaluation and reduction (safety measures) can be found in the safety design process for collaborative robots (Fig. 4). In addition, the safety measure can be selected by applying, for example, Machinery Directive (mandatory requirements), other standards and state-of-the-art knowledge. Arguments are needed to prove the solution, which is not according to the relevant harmonized standard.

Here in the collaborative robot design model risks are related to impact, clamping, shearing and stabbing. Other risks are considered by applying robot safety standards (ISO 10218-1 and ISO 10218-2). Risk reduction is made first by removing risk by applying inherently safe design, secondly by safeguarding and thirdly informing user about the risks [10]. The inherently safe design means, usually, selecting and using so small collaborative robots that they cannot hurt human. Robot selection is not here part of the process, but it is made before the collaborative robot design process (Fig. 4). The safety design process for collaborative robots is related mainly to safeguarding, which includes safety function evaluation and control and limitation of power, force, speed, stopping and area, which can be associated to Fig. 5 and phase 6 of Fig. 4. External safety devices are related to phase 3 and additional measures like enabling devices to phase 5 of Fig. 4 and Fig. 7.

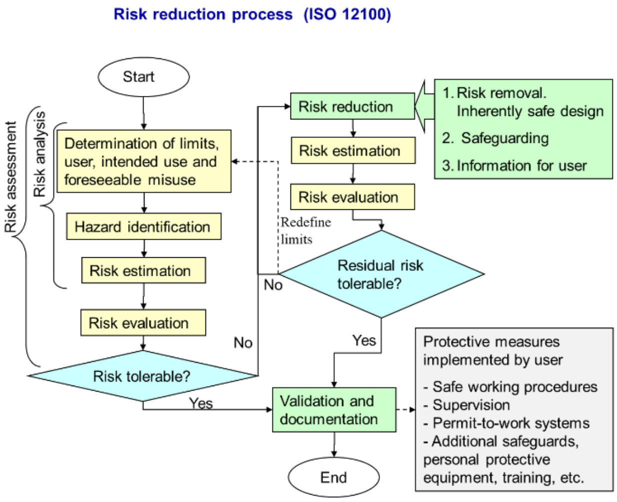

Fig. 3. Safety design process according to ISO 12100. [10]

Fig. 4 describes safety process for helping risk evaluation and reduction i.e. selecting safety measures. Fig. 5 presents the safety process related to internal safety functions. Light green means question and the track branches to two tracks (Yes/No). Light blue colour refers to action and other colours refer to specific colour coded phases. Here are explanations to the numbers/phases related to the figures:

1. Beginning of the process. There is a collaborative robot, with safety functions i.e. robot for the application is already selected. In addition, risk analysis is already made for the robot cell. First, consider impact to the head and are there sharp edges or tools, which cause hazards.
2. Do the safety functions fulfil the ISO 10218-2 section 5.2.2 requirements (PL d and Cat 3)?
3. If internal safety functions are not adequate, then apply external safety devices. These can be related to e.g. dynamic safety system, external tactile sensors, external safety-rated monitored stop or area restrictions and isolation (see Fig. 6).
4. Use PL assignment (risk assessment) for the application to see, if it gives lower requirement than PL d (see Fig. 8).
5. Can additional measures justify e.g. PL d, Cat 2. After phase 5 return, back to previous question, and furthermore to relevant phase (see Fig. 7).
6. Internal safety functions can be applied, if they fulfil safety requirements. Internal safety functions are related to e.g. impact forces, restricted area, speed or safety-rated monitored stop (see Fig. 5).

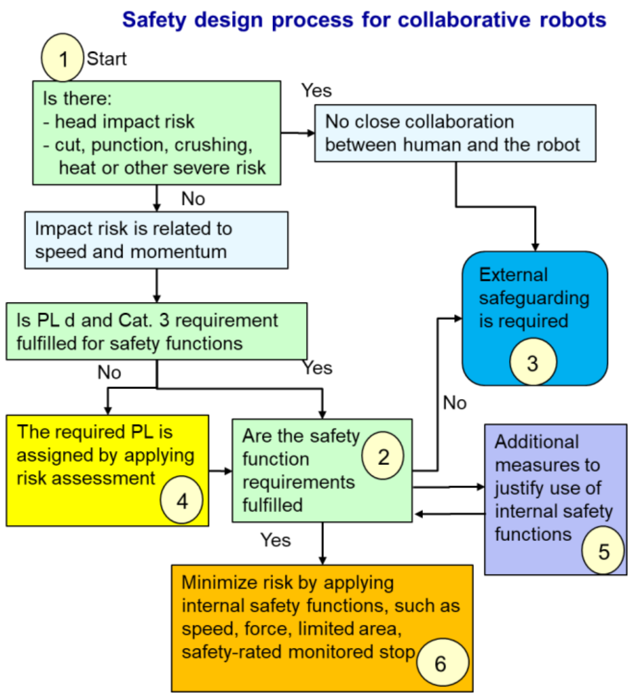

Fig. 4. Basic safety process for collaborative robots to select safety measures.

Fig. 5 shows the situation when Fig. 4 process leads to phase 6, which is related to internal safety functions.

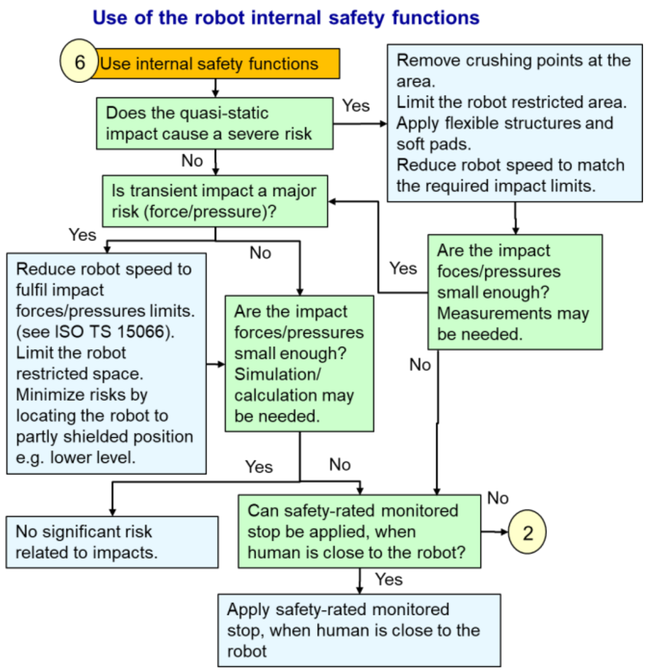

Fig. 5. Safety process for collaborative robots related to mainly internal safety functions (phase 6).

Fig. 6 shows external measures, which can be used to ensure safety. It is associated to phase 3 of Fig. 4. The measures can be valid also for industrial robots, except for external tactile sensors. Separation distance monitoring requires typically safety system, which monitors both robot and human movements, with adequate safety measures. An example of safety system is VTT dynamic safety system [12, 13]. Isolation of the robot restricted space is typical means for industrial robots and it provide only limited collaboration between human and the robot.

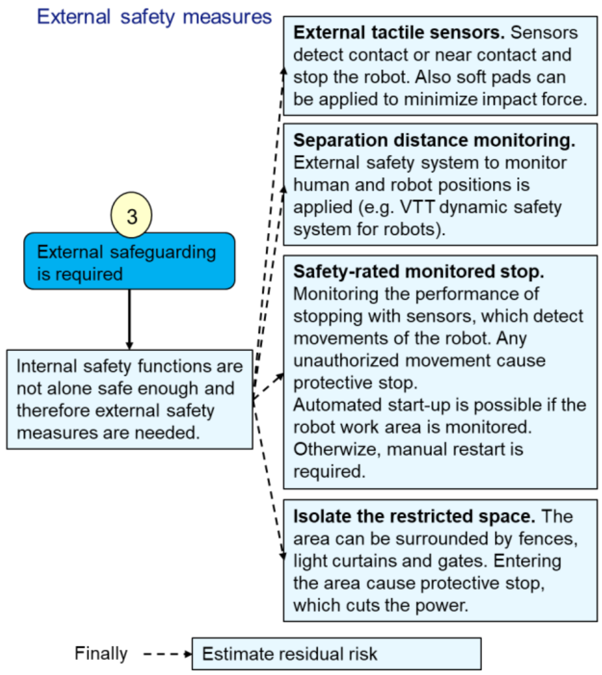

Fig. 6. External safety measures for the robot (phase 3).

Fig. 7 describes additional measures to reduce risk in order to decrease safety requirement level for the primary safety function. This phase is applicable only if the risk reduction need is small. In this phase, electronic safety functions are not applied, since PL is defined before safety functions can be applied. If safety functions are applied in this phase, they need to fulfil safety requirements of ISO 10218-2 (PL d and Cat. 3). Enabling device must fulfil the requirements stated at ISO 10218-1 [9].

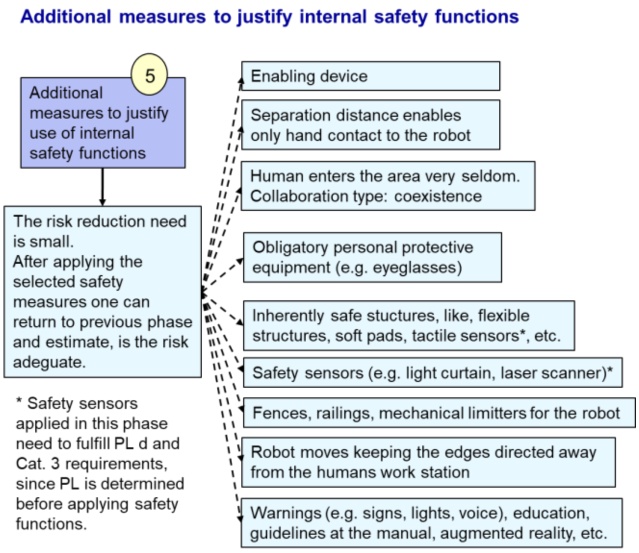

Fig. 7. External safety measures for the robot (phase 5).

Usually, the PLs of ISO 10218-2 are applied for safety functions. They are valid for typical robot applications. However, in some applications, the risks can be different and the PLs need to be reassigned. In practice, it means that severity is low and the robot cannot hurt a person. In phase 4, some severe risks are already ruled out and they are dealt at phase 3. Phase 4 is described at Fig. 8. In this phase the risk graph of ISO 13849-1 is applied to assign the PL. It would be possible to apply other functional safety standards in assigning PL or SIL, but apparently, ISO 13849-1 is here the most applicable. In some cases, there are other machinery standards, which gives performance level for specific safety functions (e.g. stability), but then one should consider how well they are applicable for the robots. After phase 4 one need to return back to phase 2.

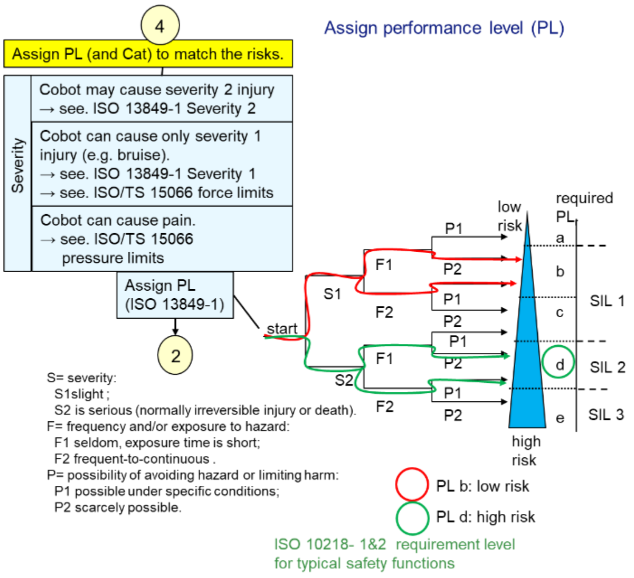

Fig. 8. Assign performance level (PL) (phase 4).

6 Discussion

It was mentioned already at the introduction that risk assessment is difficult for cobots, since close collaboration between human and robot is expected. It is relatively straightforward to isolate a system, but when safety-rated monitored stop or separation distance is applied, then also functional safety requirements are essentially relevant. When power and force limitation is applied, then, in addition, measurements or calculation models are needed to validate the applied impact force limits.

The stopping performance of the cobot is complex and, therefore, simple force limits of the robot controller do not give accurate results. According to Braman, power and force limiting is the main form of collaboration [14] and therefore it is important to consider the force limits. Currently the ISO TS 15066 provides force/pressure limits to validate cobot application. However, many aspects affect the measurement results and the measurement conditions are not yet defined in standards. The force limits face, currently, several problems: what is the right force limit for each body part, how do persons feel the impact force (sensitive vs. robust persons), how to measure the force, how the robot manufacturers can realize exact force limits in all situations. Same and, actually, more difficult problems are related to pressure limits.

The cobots can be placed also on a mobile platform and then they are mobile robots. Mobile robots can be also without additional robot on a mobile platform/robot. There are not yet standards for the safety of mobile robots and therefore the requirements need to be found from other standards, Machinery Directive and risk assessment. The amount of risks is typically larger for mobile robots than cobots, since mobile robots can be applied in many places during one work cycle.

One specific problem is related to impact to the head. According to ISO TS 15066 impact to head or sensitive body regions shall be prevented whenever reasonably practicable [7]. In most of the applications human could stick his head into dangerous impact position - The question is: What is reasonably practicable head impact prevention.

Apparently, the cobots are developing and some current issues may be solved in the near future. Currently functional safety level is not adequate for many robots, but in the near future inherently safe structures or adequate safety functions will solve the problem. The impact forces/pressures may be measured, with simple cheap device or expected impact forces could be simulated accurately. Currently, some cobots have long delays in stopping performance and it cause long separation distance between human and robot. Long stopping time affect also impact forces. True collaboration between human and cobot require quick stopping, which is related to good brakes or motion control. Quick stopping may affect structure durability, cobot's stability and load stability, and therefore the stopping performance needs to be optimized also in the future.

Although cobots are often considered to be safe, risk assessment is required to ensure safety. Hazard identification is obligatory phase, but if the risk is similar to the risk described in harmonized standard, then the risk estimation and risk reduction can be adopted from a harmonized standard i.e., usually, ISO 10218-2. All phases of the risk assessment need to be done, one way or another.

VTT Technical Research Centre of Finland Ltd. is developing in the NxtGenRob project the optimum ways to utilize next generation robotics in Finnish industry by developing solution models, design practices and (by evaluating) demonstrations from different perspectives. The main funder of the project is Business Finland Oy. In addition, seven companies have supported the project.

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