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Human – Robot collaboration in industry

Article in MM Science Journal · June 2016

DOI: 10.17973/MMSJ.2016_06_201611

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of safety it is necessary to alert with sound and light alarm (1) and stop the robot (2). More advanced systems can provide compliance control (3) – adjusting the movement by pushing it off. The most sophisticated is the entire elimination of collision by adjusting the trajectory of the movement (4).

With the growing level of cooperation, workspace of the robot and laborer is shared more until they are eventually completely unified – see Fig. 4. Standard robot cell has a fixed barrier or a virtual one in the form of a scanner or light curtain (1) to prevent human contact with the machine. A higher form of cooperation is sharing the workspace with robot's exclusive movement under the condition that the human is not present in its workspace (2). The most advanced is the simultaneous motion (3).

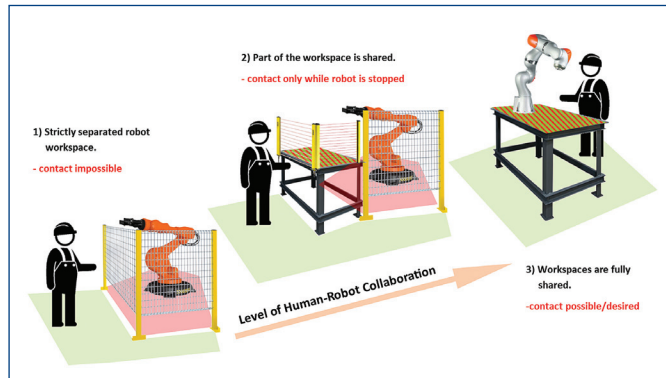


Figure 4. Shared workspace of a human and a robot

3. TYPES OF HUMAN – ROBOT COLLABORATION

In the safety standard ISO EN 10218 for robots and robotic devices are defined four basic types of HRC. For some types of cooperation, it is necessary to use special collaborative robots with embedded sensors. Other types of applications count with a conventional robot with upgraded sensors and control.

Safety-rated Monitored Stop is the simplest type of collaboration. There are applications where the robot shares a part or all of its workspace with an operating staff. In the case of a worker appearing in the robot's workspace, the machine is stopped and stands by until the man goes away. In the shared area the robot and the operator can work but not at the same time.

We can find this type of cooperation in the manual insertion of objects to the robot's end-effector or the offtake position from which the robot collects the part. Another example is the visual inspection which can be necessary while in operation. There can be operations where human presence is required such as a finishing operation or complex procedures expensive to automate. Robots can also help the operator with the manipulation of heavier payloads.

In the process of *Hand Guiding* by the operator, the load of the robot is compensated to hold its position. The operator can freely move with the manipulator in the space without an exertion of any bigger force. The human gets directly in touch with the machine but the motion is not initiated by the robot, it is just guided by the operator. Because of safety, the speed of the robot is decreased and it is upgraded with safety elements. The robot has to be equipped with a measurement device to monitor the impact load. Some robots have sensitive elements – torque sensors – embedded directly in their joints. For this type of cooperation, a standard robot can be also used. The robot has to be equipped with a sensor detecting external loads. This sensor is placed on the wrist of the robot between output interface and end-effector. It measures and evaluates the load and controls the compliance of the robot.

To increase the safety, there is an enable button (Dead man's switch) in the place of grabbing. The robot can be moved only if the button is pushed, in other case the robot is stopped. The robot can make the ergonomics better in the matter of lifting heavy payloads and the

operating staff only has to deal with a small guiding force. Hand guiding is used in case of a coordinated motion of semi-automated operations or during programming of the robot. Positions of the desired trajectory are learned according to the guidance of the manipulator by the operator.

With *Speed and Separation monitoring*, the workspace of the robot cell is divided into several areas. These areas are inspected with scanners or a vision system. In areas out of the reach of the manipulator where the operator does not get in contact with the robot but can be endangered with a dropped manipulated object, the robot is slowed down to a safe speed. If the robot's workspace is breached, the robot is stopped. As far as those two areas are clear, the robot can operate at maximal parameters. The speed and position of the robot are continually monitored. An advisable application can be at a work station where the robot operates at maximal parameters but operating personnel has to enter the area in a specific time e.g. because of logistics issues either to place or take away the product.

Power and Force Limiting is a type of cooperation where special collaborative robots are needed. Motion parameters of robots are monitored with high precision and even a tiny deviation from the actual position compared to the programmed one can be detected. Precise encoders with high resolution allow the robot to precisely monitor its speed and position. Forces and torques are measured and evaluated with sensitive torque sensors in joints of the robot, by analyzing the electric current drawn by actuators, by measuring reactions transmitted to the ground or with tactile sensors. The robot is therefore capable of identifying the impact into the obstacle, to analyze it in extremely short time and react. The robot can apply the brakes after collision and stop immediately, alternatively make a counter-motion in opposite direction to decrease the impact energy as much as possible.

By using special collaborative robots, a real human-robot collaboration can be achieved. Typical applications are composition and assembling units made out of small pieces, for example in electronics industry. The robot can place objects into precise slots where real-time corrections of position are needed thanks to its sensitivity. The robot is also capable of following the contour of the surface by applying specified force. This can be used for polishing.

4. SAFETY OF COLLABORATIVE ROBOTS

The presence of a man in the area where heavy robotic arm is moving at high speed urges to deal with the issue of safety. Standard robots are available in warning colors and surrounded by a fence. When the operational range of the robot is disturbed, the robot is stopped immediately to avoid harm or even a fatal injury. If the robot is manipulating with payloads weighing up to several tons, or with acceleration 10g, then it has to be sufficiently secured and the presence of any personnel is out of the question. To achieve safe human-robot collaboration we have to make do with a compromise. Maximal payload and velocity of the motion are distinctly decreased. The load capacity of collaborative robots is around 10 kg and maximal velocity of the motion is limited to 250 mm per second. The robot can be lightweight due to these limitations. Light design does not cause as much damage after the impact as a standard robot. However, even those limitations are not sufficient. The robot has to be upgraded with sensors detecting, alternatively preventing collisions.

Manufacturers have chosen different strategies to assure safety of their products. On the figure – Fig. 5 are a few examples of collaborative robots. First two of them on the left are modified conventional robots equipped with passive and active safety elements. The robot in the



Figure 5. Collaborative robots – MRK-Systeme KR SI, Fanuc CR-35iA, ABB YuMi, UR5, KUKA LBR iiwa

middle has similar working range and parameters as a human laborer. The last two are special lightweight robots with embedded sensors.

Active elements of collision detection were mentioned in the paragraph regarding *Power and Force Limiting*. New reactive control strategies are developed and tested as sensitive bumper skin [Frigola 2006]. Some robots have a sensor cover which can detect the obstacle before the collision itself due to capacitive sensors. Collisions can be also predicted with vision systems. In this type of application is a demand for a very fast response.

If the collision occurs, the robot is equipped with elements of passive protection and its design is adapted to minimize the damage. Collaborative robots have no sharp edges and all of their dangerous parts are rounded. Cobots have no parts where fingers could be pinched as a consequence of rotation. Surfaces are softened with plastic materials. Some parts are made of plastic or coated with a soft foam material which is able to absorb some energy of the impact. This leads to increased safety. Cables and compressed air hoses are placed in the inner space of the robot or they are covered so that the risk of dangerous interception is minimal.

In terms of safety of cobots, it is important to realize that active safety elements must be set up correctly. In case of a wrong setup, robots can reach attributes of standard robots. They can move at high speed and the impact energy after a collision is many times higher than the safety limit! It is necessary to set up right limits during programming. If those limits are overrun the robot reacts or stops. An important parameter is the robot's actual manipulated payload because it enters the calculation in a dynamic model. The programmer of the robot is responsible for a significant part of the workplace safety.

The safety of the robot is closely related to safety of the technology placed on the end of it. Everything what is fastened to the robot can decrease its safety. This can apply to cables mounted to the robot surface, vision system but mainly the end-effector. Robot becomes dangerous when it is manipulating with an object with sharp edges or pointy parts. Other dangerous objects may be a drilling or welding head mounted to the robotic wrist. In those cases, the contact with the technology is forbidden. To achieve successful collaborative robot deployment, it is necessary to elaborate a detailed risk analysis.

5. APPLICATIONS WITH COLLABORATIVE ROBOTS

Even if the technology is still in its infancy, some companies and universities have already developed applications with cobots. KUKA [KUKA 2015] or Fraunhofer institute [Fraunhofer 2012] are combining mobile platform and cobot into agile robotic assistant which has a wide workspace thanks to its mobility. Applications are tested in both the real and virtual world and the co-presence of the robot is observed [Weistoffer 2014]. In automotive industry we can find cooperative applications in terms of Power and Force Limiting. AUDI [AUDI 2015] has a PART4you operation, where the robot raises a component from the box and gives it to the worker so that he does not have to bend. In BMW [BMW 2013] a sensitive robot is sealing doors in cooperation with humans. Fig. 2 shows application in VW engine assembly [BW 2013], where the robot inserts glow plugs into cylinders next to laborer. In SKODA AUTO [SA 2015] there is a collaborative application in Vrchlabi gearbox assembly plant – see Fig-6. The robot thanks to its sensitivity inserts the gear actuator piston into a precise hole.



Figure 6. Collaborative robots in SKODA AUTO – KUKA LBR iiwa in Vrchlabi plant (left figure), testing of UR10

During calibration of the workplace, the operator can push off the robot and it remains waiting until the workspace is clear. Robot KUKA LBR iiwa is equipped with a safe end-effector that has no sharp edges and even during loading the robot does not harm the human in any way. Another robot is tested for hand guiding application where the robot holds the part for the worker who can adjust its position and mount it.

6. CONCLUSIONS

Regarding the limited weight capacity and velocities of the robot the fundamental idea is not to replace current conventional robots but to uncover new opportunities of automation. The possibility of using the robotic workplace without safety fences can urge to utilize it in fully automated productions to decrease the amount of installation space and costs of safety barriers. The first question to the manufacturer is when will you provide higher payload robots. From the basic principle of cobots, it is possible to increase the payload in the scope of kilograms, not to levels of standard heavy payload robots. The fundamental idea of this strategy is to extend a spectrum of robotic applications to the industries which are not automated nowadays. Robots are used in the sense of robotic assistants to improve the quality of work of the human laborer. In several fields of production, it can be difficult to find a proper application for collaborative robots. We have to break away from an existing ingrained procedure of designing automation and take advantage of the cobots' flexibility. In relation with a human-robot collaboration it is necessary to focus on the field of detection and vision systems. As a source of information, we could recommend a set of e-books available on the website ROBOTIQ [Robotiq 2016].

ACKNOWLEDGEMENTS

Author is supported by ŠKODAAUTO company with which he cooperates in research of capabilities and implementation of collaborative robots in automotive industry. This article has been supported by specific research project SP2016/142 and financed by the state budget of the Czech Republic.

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