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51st CIRP Conference on Manufacturing Systems Development of a Balanced Decoupling Unit for a Safe Automated Screwing Process during Human-Robot-Cooperation

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Abstract

The paper presents an automated screwing application inside a robot cell with human-robot-cooperation. It describes the use case and how the design challenges for process reliability and safety have been addressed from concept idea to the real set up. A focus is thereby set on the safety implementation, which is enabled by the development of a balanced decoupling unit, which enables force limiting at the end-effector during physical contact. The decoupling unit is implemented for the application with the screwing tool and is designed according to functional safety requirements. Its usability is validated in appropriate force measurements (according to ISO/TS 15066) and evaluated on its performance characteristics for the productivity of the robot application.

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1. Introduction

Industrial Robots have been linked to heavy duty manufacturing purposes in its beginnings in the seventies. They have been dedicated to automated handling for high masses and high velocities but with a wide variability for its dedicated application [1]. Nowadays a growing number of industrial robots which can be operated in close vicinity to the user are becoming available, meeting the demand for flexible automation systems in manufacturing and providing enhanced ergonomics. They are advertised as collaborative robots and provide enhanced functionality for usability as well as for safety for installation in manufacturing applications as safe robot systems with humanrobot-cooperation (HRC).

Assembly lines of today are fixed monuments, set up to deal with certain known numbers of variants, defined resources and production volume. Thus, the static system is not able to handle dynamic changing production values. Consequently, resources are not used to the possible capacity or overloaded. The need of changeable assembly systems will grow in the next years [2]. Thereby HRC can not only be seen as a parallelization of operating tasks but as an enabler for changeability in the context of Industry 4.0 and as an effective mean to create flexible linked automation lines [3,4].

Robots comprise their skills for assembly processes by a stiff mechanical structure, strong motors and reliable and unfatiguing motion cycle. At the same time the human provides better performance when it comes to complex manipulation and error handling in the process. Combining both those expertises in one assembly process by spatially separated working areas for the robot and the human can only be achieved by a complex material flow system. A better option for a flexible assembly system with HRC is thereby the realization of a stationary assembly workplace with unrestricted access to the workpiece and the tooling to effectively use the capabilities of both the human and the robot [5]. Thereby intended and unintended physical contact between the human and the robot system have to be considered. Such a direct physical HRC assembly cell is presented in this paper, where the industrial use case (as described in chapter 2) leads to the implementation of an automated screwing system with a force-limiting capability at the end-effector for which a balanced decoupling unit is developed. A manual pre-assembly station is installed next to the fully automated screwing station to avoid costly feeding systems and where operator interference to the robot system has to be considered for the purpose of commissioning and trouble shooting.

Robot systems that are installed in the production are a type of machinery whose safety and health requirements are covered by the Machinery Directive (MD). Safety considerations to be applied for direct HRC are specified by the robot safety standard ISO 10218 [6] and its related technical specification ISO/TS 15066 [12]. Thereby a specific focus is set on the func-

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tional safety requirements of implemented control systems and the limitation of possible contact between parts of the robot system and the human operator.

Different implementation strategies on how to avoid collisions during HRC in assembly applications have been presented e.g. in [7–9]. To assure a remaining tolerable risk for collisions during HRC leads to the necessity of quantifying the collision potential of a specific robot system to analyse its hazard as it has been stated in several scientific contributions from the robotics research community during the last years, see e.g. [10,11]. This method, according to the guidelines of [12] is presented for the HRC assembly system in this paper in 4.

Holding the specified safety limits in potential collisions between parts of the robot systems and an operator can be achieved by reducing performance characteristics of the robot, such as speed or contact force [13]. As a safety threshold has to be met during operation at any time, a detailed investigation of the safety-productivity trade-off for an application has to be conducted to enable economic feasibility of an HRCapplication [14]. For the system set-up described in this paper, the challenge is to find the best solution for a flexible, safe and efficient robot system. Therefore an external force control mechanism is developed – the balanced decoupling unit – to enhance the safe speed during HRC for a wide variety of assembly applications.

In the following chapters the concrete industrial use case is introduced and the technical solution for its automation is derived thereof. The main focus is set on the safety concept in which the balanced decoupling unit forms the main component. Its functional principle is described in chapter 3 followed by the concept validation for the real setup in chapter 4.

2. Use Case

The industrial use case is an assembly process of three molded plastic parts, that have to be joined by a number of screws. The manufacturing process in which the assembly station is incorporated is characterised by a noticeable fluctuation in production volume and a high number of product variants. The implementation of the automated screwing process inside a cell with HRC is thereof motivated by the request for a flexible automation system without fences. Invest calculations – which are not part of this article – foster this solution for the envisaged cycle time. The concept for the balanced decoupling unit is not limited to this application but the use case serves as a real-world example for deriving the safety concerns that are associated with a wide variety of robot assembly processes.

2.1. Functional requirements

The current screwing process is conducted completely manually by one operator. The operator screws seven screws to link three injection molding parts together to one housing element within a cycle time of 30 s. All approaching movements to reach the screwing position are positioned parallel in so-called top-down movements. The screwing positions are located on different heights, in close proximity to the housing edge, while the screwing spindle has to overcome a distance up to 140 mm.

To allow safe access to the moving robot for the manual commissioning of the cell, an HRC application with a shared

workcell concept is chosen for the automation solution. This features a safety design by a well-rounded mechanical structure of the robot arm without sharp edges and corners to limit the collision potential of the robot to reduce the injury risk for an operator. Additional the robot includes a safety controller which reliable monitors velocity and axes positions.

As no external safety monitoring of the robot surrounding is foreseen for the screwing application, potential contact with an operator has to be assumed at any time in the robot process. This requirements leads to a worst-case estimation in terms of the potential collision configuration between the robot and the operator.

Considering force limits for transient contact that are proposed in [12] the lowest values, as derived from the most vulnerable body part of the human have to be considered for robot motion in free space, leading to a high restriction on the safe speed limit of the robot at any time of the process. As described e.g. in [11,15] clamping scenarios between a robot and a human body part are exhibiting an even higher risk for injuries than contact in free space. Therefore even lower speeds have to be assured when the robot system operates close to the workpiece. Specific considerations for accessibility of specific body parts will be presented for the application on hand in the following chapter. Contact risks will be thereby evaluated for the robot as well as for all its peripheral components.

According to the requirements, the technical concept of the application has four main areas in which to provide measure to rate the performance of the system:

- Enhancing safe robot speed (cycle time)
- Detection of clamping in top down movements (safety)
- Minimization of robot movements (cycle time)
- Enabling of changeability through modularity (flexibility)

2.2. Technical concept

The robot for the installed HRC system is mounted on a passively moveable platform to enable flexible placement of the automated assembly station within the production line. A screwing unit with an automated screwdriver is mounted to the flange of the robot. The screwdriver is extended by a 140 mm long screwing spindle. The screwdriver with the spindle is additionally mounted on a linear guidance which is actuated by compressed air. With this so-called extra stroke it is possible to reach all screwing holes on the workpiece.



Fig. 1. Robot system for assembly with automated screwing unit.

The robot platform is enhanced by a so-called "backpack" platform. It hosts the electrical and pneumatic cabinets for controlling the mounted screwing unit and can be mechanically connected to the robot platform. A safety PLC for controlling the process logics and the controller of the screwdriver are installed in the electric cabinet, while the pneumatic circuits are placed in the pneumatic cabinet. The complete robot system with the two passively mobile platforms is illustrated in Fig. 1.

The screws are provided by an external separation unit installed next to the robot platform. The screws are loaded via a tube to the tip of the spindle by a blow feeding system. The screw is fixed to the tip by vacuum. The blow feeding system for automatic reloading of the screws during robot positioning reduces process time by saving the movements to a pick position for the screw.

The screwing process for each screw is divided into six subprocess steps, as described below and depicted in Fig. 2:

- 1. Robot movement to approach position
- 2. Robot linear movement in z-direction
- 3. Linear actuation of screwing spindle
- 4. Screwing
- 5. Screwing spindle back to home position
- 6. Robot movement to approach position



Fig. 2. Screwing process sequence.

3. Safety Concept

After the technical concept and hardware and control components have been defined possible hazards within the automated screwing application will be identified to perform the corresponding risk analysis.

3.1. Overview of hazards

The safety principle for the screwing application follows the requirements as provided by [6] as the collaboration type "Force and power limiting". Thereby it has to be ensured that potential collisions between the robot and the human during robot motion have to be limited up to the proposed force and/or surface pressure limit. Due to the nature of the underlying application the main injury here has to be expected during contact with the moving robot system or clamping between moving robot system parts and stationary equipment. The specific body regions and collision configurations affected within the application have to be examined for this purpose.

When the robot executes the movement to the approach position above the workpiece, impacts with an operator in free space have to be considered as potential hazards. The according safety measure is to limit the speed of the robot motion and to cover all possible contact surfaces at the tooling to damp the contact effect. To estimate the safe robot speed for motion in free space (for blunt surfaces and without clamping hazards) during HRC [12] provides the following estimation for the maximum velocity:

$$v_{max} = \frac{F_{max}}{\sqrt{\mu \ k}} \tag{1}$$

This maximum speed depends on the required force limit F_{max} of the specific body region, the reduced mass μ of the robot arm with additional load on the contact location and the contact stiffness *k* (resulting from the stiffness of the body region and the robot part surface). For the underlying application this results in a maximum speed of 400 mm/s under the pre-assumption that contact with the head is excluded. Further bumper material might be applied to further reduce the impact energy and therefore enhance the limit for safe speed.

Another hazard can be identified for unexpected robot motion when the screwing spindle is not stored in its home position. The safety measure in this case provides a safe monitoring of the home position of the screwing spindle provided by a contact switch. If the safety switch is not contacted, the robot mode changes to standstill monitoring. An unexpected start of robot motion would result in a stop category 0, according [6].

All hazards that are related to clamping of body parts with parts of the robot system are holding a higher injury risk for the operator. If clamping occurs the robot system has to detect this situation in due time to stop all hazardous robot motion before critical force and/or surface pressure limits as given in [12] are exceeded. Thus, these hazards again directly effect the robot speed and the resulting cycle time of the application. While safe speed for contact in free space can be reliably estimated as presented above the maximum speed for which clamping limits can be met highly depends on the configuration dependant stopping behaviour of a specific robot system. As generically valid simulation tools are not yet available (see e.g [16]) force and pressure measurements have to be conducted which can only be provided for the installed application (if other experimental data is not yet available).

The most critical hazard of the described screwing application occurs when the system is in the sub-process step 2 (see Fig. 2). While the robot executes the linear downward movement an operator can reach between the small tool tip and the workpiece. Clamping of a hand, an arm or a finger can thereby be possible. State of the art robot systems – even with integrated force-control – have to reduce their safe speed – maximum monitored speed – to a very low level to compensate for this hazard. Higher safe speed can only be achieved by additional (external) contact damping, which is realised here in form of the developed balanced decoupling unit, as described in the next chapter.

3.2. Development of balanced decoupling unit

It has been stated in several scientific contributions (such as [11,15]) that speed reduction without additional forcesensitivity of the robot is a reliable mean to minimize the collision risk at transient – non-clamped – contact. In the case of clamping a contact-reaction is required to respond to the exerted force during contact, as e.g. provided by integrated or external force-controls for robots. Such force-controlled robot systems trigger a stop of the robot which results in a remaining clamping of the affected body part which is then exposed to a constant clamping force. A safety strategy is required to release the operator. For most cases the resulting safe speed of the robot can thereby not exceed 50 mm/s to meet the maximum allowed forces and pressure.

To overcome this speed limitation which has been experienced for several real-world installations of HRC the paper introduces a decoupling unit to detect a clamping situation for the most critical movement, the movement in downward direction. The decoupling unit is realized as a linear slider between the robot flange and the tool, in this case the screwing unit. The principle of the decoupling unit is shown in Fig. 3.



Fig. 3. a) Linear approach downward b) Displacement of balanced decoupling unit during clamping.

The decoupling unit has to fulfil two functional requirements. The displacement has to be detected and furthermore, during screwing, the decoupling unit has to be locked for a stable screwing process. In Fig. 4 the functional components which realize these requirements are shown. A position sensor at the tool mounting position is integrated to detect the displacement of the plate. The sensor sends a stop signal to the robot controller. It acts comparable to a classical protective door locking switch.

The plate is guided on two linear slides and is connected to a pneumatic cylinder. The pneumatic cylinder in the top of the unit is responsible for locking the decoupling unit with the locking pressure p_1 . The locking is only actuated when the robot is at its final approach position and while standstill of the robot axes is monitored.

The decoupling unit has the essential advantage that a clamped person can release its trapped body part by pushing the tool away from the clamping position. The stopping distance of the robot after receiving the stop signal from the position switch is buffered within the linear guidance. It can be expected, that the remaining constant clamping force in the quasi-static case is equal to the weight of the screwing unit.

The screwing unit itself has a weight of about 10 kg, which leads to a constant clamping force of about 100 N. Thus, to



Fig. 4. a) Sketch of functional components (front view) b) CAD model decoupling unit (side view).

reduce the force, the decoupling unit is provided with an additional functionality. The pressure p_2 in the lower chamber of the pneumatic cylinder is used to balance the weight of the screwing unit. The principle is sketched in Fig. 5. The force F_p can be set equal to the weight force F_G of the tool and the friction force within the pneumatic cylinder. In reality F_p shall be chosen in a way that the unit is not set into a swinging motion due to movements of the robot arm.



Fig. 5. Principle of internal balancing.

The principle of an external balancer is introduced in [17]. The external balancer described in the patent is used to reduce the payload of a tool. Thereby a heavy tool can be mounted to a robot providing a lower payload only. In case of the decoupling unit developed for safe HRC an internal balancer with compressed air is designed to reduce the clamping force. It is expected that the safe velocity of the robot can thereby be increased and that the constant clamping force converges to zero. According to the requirements for functional safety in [18] with a required performance level (PL) d with structure category 3 for robot applications (see [6]) the pneumatic cylinder is safety relevant and has to be monitored.

Therefore the two pressures in the pneumatic cylinder are monitored by a safe sensor system. Redundancy is enabled by implementation of two different pressure sensors. If a pressure in the chamber is out of range or the two sensors have different outputs the robot is blocked from motion. For an industrial application it can be required to check the functionality of the balanced unit in certain time steps.

3.3. Implementation of safety program

Beside the mechanical design and construction several safety measures control the activities of the robot system. A fail-safe PLC collects all safety sensor signals and processes the information to the robot controller. The robot controller is connected via ProfiSafe to the fail-safe PLC. The robot controller provides several safety functions [19] for position and speed which have to be activated according to the sensor signals of the safety components.

The main safety circuit contains the monitoring of the displacement of the decoupling unit and the pressures within the chambers of the pneumatic cylinder. If one of the three safe sensors detect a deviation to safe state the robot receives a stopping signal, a stop of category 1.

Motion of the robot arm in free space has a higher safe speed than the linear downward movements towards the workpiece. Both velocities are implemented in the robot program, but have to be monitored by the safety controller. In a workspace with a defined distance between the robot system (tool or robot arm) and other parts (e.g. the workpiece) in a range between 120-300 mm the velocity is allowed to be up to 400mm/s (safe speed in free space). This is due to the fact that this gap does provide enough clearance for arm, hand and finger of a person as stated in [20].

Below 120 mm clamping of arm, hand and finger is possible and safe speed for clamping has to be selected. If the gap is wider than 300 mm a reach in of the head is also excluded. To derive the safe speed for clamping, which is needed as the robot tool has to reach to screwing holes force and pressure measurements have to be conducted. The measurement set-up is demonstrated in Fig. 6. The robot executes linear downward movements with different velocities against a stiff dummy workpiece. The evaluated speed ranges from 25-250 mm/s. The maximum allowed force for the evaluated arm, hand or finger collision in transient contact is 280 N and in quasi-static contact 140 N. The pressure limits are 180 N/cm² (quasi-static) and 360 N/cm² (transient).

As a force measure device the KMG-500 [21] is used and it is positioned for the measurement on the workpiece. The provided Fuji Prescale foil to measure the maximum surface pressure during contact is placed on the measurement device. Appropriate damping material to account for the body part stiffness and to smooth deviations in the metal-metal contact are placed between the contacting parts.

The results of the measurement with different robot velocities are provided in Fig. 7. The contact forces are not critical compared to the quasi-static limit until a linear speed of 200 mm/s. The diagram plots the maximum transient contact forces achieved in the measurement over the robot speed. As a limit, the transient force limits are selected, due to the fact that the force-time curve – see Fig. 8 – shows that the contact force falls back to zero within a few milliseconds, thereby revealing the characteristics of a free impact. The expected advantage of the balanced decoupling unit is therefore verified. At a collision speed of 250 mm/s the displacement of the decoupling unit reaches its mechanical limit. Thus, a constant clamping force is indicated to the force measurement device.





Fig. 6. Measurement setup for clamping situations.

Fig. 7. Contact forces and surface pressure for different linear velocities.

After set-up of the HRC robot screwing assistant, it is required to analyse the possible clamping positions on its forces and surface pressure during the robot process. Thereby the safe speed for the downward motion close to the workpiece can be determined and documented for the risk assessment. In addition, the cycle time for the screwing process sequence can be measured to quantify the productivity of the application.

4. Validation

In fact the surface pressure is more problematic and reaches already for a linear speed of 75 mm/s the safety critical zone for HRC as illustrated in Fig. 7. The pressure thereby depends on the minimum size of the contact area in the clamping event. Thus, with the current installation a maximum speed of 75 mm/s for the downward motion is considered as safe speed. The force and pressure limitation for static clamping situations is a function of balancing pressure p_1 , linear velocity of the robot and the size and shape of the contact area.



Fig. 8. Time behavior of contact force during collision.

Therefore a maximum robot speed of 400 mm/s in free space and 75 mm/s for the downward movement is implemented in the robot program and as the monitored safe reduced speed for the safety controller. As a result one complete screwing cycle takes about 7 s. Consequently, only four screws can be assembled to the molds within the required cycle time of 30 s. At this point of development there is still a potential for optimization in terms of cycle time. Increasing the surface with a cover around the tool tip, a speed of 100 mm/s for linear approach is expectable and realistic.

5. Summary and outlook

The article presents an automated screwing system with direct HRC. To compensate for potential collision risks safe speeds have been derived for free motion and clamping areas. The safety controller of the robot, round shaped tooling and the developed balanced decoupling unit have been presented together with its integration into a safety reliable process control. The robot system is able to execute four screwing operations within 30 s while keeping safe force and pressure limits as provided by robot safety standards. The derived safe speeds are validated by the presented collision measurements.

As a summary for the development of the decoupling unit it can be stated that the system component fulfils the expectations in reducing constant clamping forces to zero. Thereby trapped body parts can easily be released while sufficient stiffness can be sustained for the screwing when the appropriate position is reached. The unit is deployable for different types of robots which provide a safety controller with position and speed monitoring functions. The robots safety functions can be extended thereby with a highly reactive one-directional clamping detection functionality. The unit is also usable for other assembly processes like pick and place operations or assembly tasks with small forces, e.g. a gripper can be mounted instead of the screwing unit.

To achieve a higher productivity in the next step the application can be extended by external workspace monitoring, e.g. a laser scanner to monitor human access. When no human is close to the robot, the robot can move with higher speed according to minimum safety distances. If a worker enters the monitored space, the robots slows down to the speed configuration introduced in this paper. The screwing process can then still be performed with the lower productivity.

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