APPLICATION OF SPEED AND SEPARATION MONITORING TECHNIQUE AT AUTOMATED ASSEMBLY PROCESS

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The realization and implementation of a collaborative robotic system in the automotive industry has many advantages in productivity, product quality, and worker ergonomics, but worker safety aspects play a crucial role in these activities. This paper presents the results of ongoing research into developing an automated workplace for an assembly of industrial limit switches based on the cooperation between human and robotic systems. Operating speed and worker-robot separation monitoring methodology (SSM) was used as one of the available methods to reduce the risk of injury according to the technical specification ISO 15066 on collaborative method sharing space with humans. The virtual environment simulation aims to determine the SSM algorithm's parameters to estimate the minimum protective distance between the robot and the operator. The cooperation between the human and the robot and the safety issues specified by the SSM system assumed operational safety and reduced the operator fatigue during the assembly process.

KEYWORDS

Speed and Separation Monitoring, Robotic System, Assembly Process, Simulation, Safety

1 INTRODUCTION

In the industrial field, man and the robotic system usually work separately to avoid collisions. Applications that reduce potential human error are ideally suited to an industrial automated system. The robotic system makes it easier to reach hard reachable places, achieves incomparable accuracy and speed, and relieves people from repetitive work. On the other hand, man is more flexible and adaptable to new or adverse situations and has incomparable sensorimotor capabilities used in other sectors (such as surgery, orthopedics, and others). The constant development and growing trend in robotics are shifting from the individual and local deployment of industrial robotic systems to the group building of a collaborative workplace of type person vs. robot, the most commonly in SMEs. The automation of these enterprises is often lower than MAS enterprises.

The main reasons for the deployment of these workplaces include increasing the degree of competitiveness, especially if we need the short life of the final product and excessively high costs for fully automated robotic systems. Replacing hard and lengthy manual work of a person with flexible, cooperative work meets the requirements of capable and skillful employees, who can then cope with more qualitative thought tasks. Other side effects include excessive customer demands when employees have to work overtime due to overproduction, or there is a need to recruit additional staff at a time [Vysocky 2016].

At present, the application of collaborative robotic systems in the automotive industry has increased dramatically, especially on assembly lines. Many industries and application areas were automated, although there are still many challenges in implementing this type of automation that remain unsolved. Many tasks have a repetitive nature in automated workplaces, such as screwing or precise placement of objects. The idea of collaborative workplaces is to fill the gap between manual and fully automated processes. Collaborative robotic systems can be a solution to help the operator perform complex repetitive tasks. Robotic systems can help operators share tasks and increase productivity, leading to improved efficiency and safe performance [Pires, 2019]. Collaborative workplaces at the same time and space have many hazards and risks related to operator safety. For this purpose, ISO has described four different scenarios (TS 15066) to increase security with this type of robotic system:

A. *Safety Monitored Stop*. In this case, the robot usually works alone and stops when the operator enters its workspace. This collaboration feature is suitable when a worker performs a precise operation on a workpiece while the robot is still working on it.

B. *Hand Guiding*. The operator who leads the movements of the robotic system shows its trajectories by guiding his hands. This type of collaboration allows for faster path learning without programming the robotic system. It is especially suitable for small production or tasks that are difficult to automate.

C. *Speed and Separation Monitoring*. In this case, the robotic system adapts its speed relative to the operator's location in the shared workspace. Three safety zones are defined (green, yellow, red), and a vision system or sensor controls the operator's position. If the operator is closer, the robotic system works slower. When the operator is too close to the robotic system (i.e., in the red zone), the robotic system stops.

D. *Power and Force Limiting*. These robotic systems use limited power and force to feature an embedded and programmable electromechanical system that allows control forces and torques to operate within an acceptable level of risk in all reasonably foreseeable modes. These robotic systems can work with humans without the need for additional safety devices (considering risk assessment).

2 SPEED AND SEPARATION MONITORING TECHNIQUE

We achieve the different safety zones by this type of collaboration delimited in the robotic system workspace. Certain zones allow maximum speed for the robotic system, although some zones will require lower velocities due to the potential proximity of the operator. Other zones stop the robotic system completely, usually because the operator is very close to the robotic system. Restoring the working cycle is automatic. Such separation distance violations are not recorded statistically in the control system. The monitoring of the safety zone is performed by various monitoring systems, primarily by sight or a sensor [Vagas 2016]. The safety zone can be of any size and geometry. The user sets different zones and assigns additional acceleration and speed settings to these zones to ensure that the robotic arm does not harm the operator under any conditions.

It can happen when collaboration between humans and robots is not constant and when the robotic arm will work alone, at full speed most of the time. Doing so can speed up the assembly process and still allow operator-robot collaboration. For example, in the case of screwing with the robotic arm, the container must be filled by the operator while the robotic arm still performs its process. However, we must consider the following conditions:

A. Maintaining the minimum protective separation distance between the operator and robotic system at all times.

B. Using of requires protective devices to determine the approach (reduction of the protective distance).

C. Reducing the speed (from a safety point of view) to maintain a minimum protective distance.

D. If we cannot guarantee the minimum safety distance, a safety stop is required.

The equation for calculating the minimum protective distance for cooperation between human and robotic systems based on ISO/TS 15066 is an extended version defined in ISO 13855 to determine the protective distance for non-mobile machines. According to the ISO/TS15066, the minimum protective distance, (S), at the time (t_0) is from the formula:

$$S_p(t_0) = S_h + S_r + S_S + C + Z_d + Z_r \tag{1}$$

Where S_p is the minimum protective distance; t_0 is the „now“ time; S_h is the extra distance to change the position of the operator's; S_r is the added distance for the reaction time of the robotic system; S_S is the added distance for the braking distance of the robotic system; C is the distance of the body part of the operator in the direction of the danger area of the robotic system before the reaction of the safety element (prescribed distance according to ISO 13855); Z_d is the positional uncertainty of the operator in the cooperating space (measured by the sensing device and its measurement tolerance); Z_r is the positional uncertainty of the robotic system (resulting from the accuracy of measuring the position of the robotic system) [ISO TS 15066, 2016].

We use the linearized form of equation (1) to calculate the minimum allowable distance S between the human and robotic system under static conditions.

$$S = (v_h \times T_r + v_h \times T_s) + (v_r \times T_r) + B + C \tag{2}$$

where v_h is the speed of operation, including direction to the robotic system in the shared space (speed may be positive or negative, depending on whether the separation distance increases or decreases); T_r is the reaction time of the robotic system (including the time required to detect the position of the operator, processing this signal, activating the stop of the robotic system, but the stop time itself is not counting); T_S is the time required to stop the robotic system when the stop signal is activated (it is not a constant, but a function of the robotic system configuration, planned movement, speed, and load); v_r is the speed of the robotic system (including its direction towards the operator in the shared space, and maybe positive if it approaches the operator, or negative if it moves away from the operator); B is the braking path of the robotic system, which contains $Z_d + Z_r$

The value S_p (t_0) dynamically calculates the safe separation distance. It allows the value of distance to vary depending on the speed, but we can use it as a fixed value in the worst case. Formula (1) considers the combination of moving parts of the robotic system and the operator in the shared workspace. The nearest part of the robotic arm and the operator can move away from each other, while another part of the robotic system can move closer to the operator. The added safety distance for changing the position of the operator S_h is as follows:

$$S_h = \int_{t_0}^{t_0+T_r+T_s} v_h(t)dt \tag{3}$$

Where "t" is the variable for the mathematic integration.

The constant value for S_h at an estimated human velocity of 1.6 m.s^{-1} can be as:

$$S_h = 1{,}6 \times (T_r + T_s) \tag{4}$$

The added safety distance for the reaction time of the robotic system S_r is as follows:

$$S_r = \int_{t_0}^{t_0+T_r} v_r(t)dt \tag{5}$$

The constant value for S_r can be estimated as follows:

$$S_r = v(t_0) \times T_r \tag{6}$$

The added safe distance for the braking distance S_s is given by:

$$S_S = \int_{t_0+T_r}^{t_0+T_r+T_S} v_r(t)dt \tag{7}$$

S_s values can explain the ISO 102018-1 standard. For sufficient protection at time t_0, the measured protection distance S must be greater than or at most equal to the minimum protective distance S_p:

$$S_{measured} = (t_0) \geq S_p(t_0) \tag{8}$$

The graph of the robotic system stopping use its speed and distance from the operator can be seen in Figure 1.

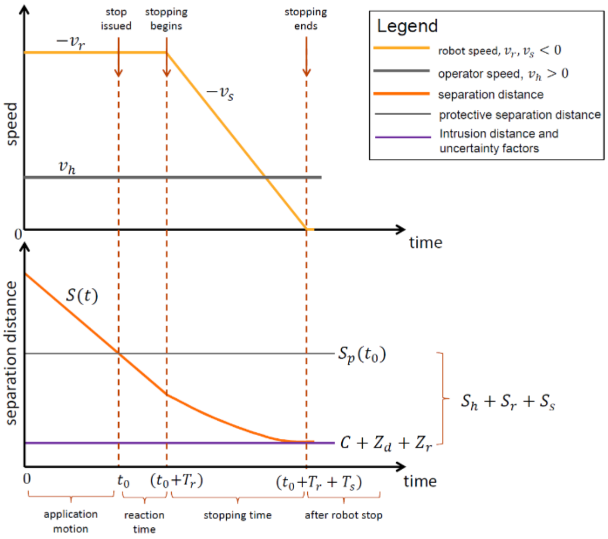


Figure 1. The graph of the robotic system stop based on its speed and distance from the operator [ISO/TS 15066 2016]

3 EXPERIMENTS AND RESULTS

Assembly activities are an integral part of automated processes where collaborative robots are the crucial part. Our logical step was the experimental verification of such tasks in laboratory conditions on such an assembly object, which can be manufactured, used, and put into practice. Future research expects to deploy this solution into similar automated workplaces to assembly activities.

The sequence of the assemblies is an integral part of process planning. Its role in the initial phase of product design is crucial for optimizing the manufacturability of the product and the design process itself [Hricko 2018]. It plays a fundamental role in both product assembly and process assembly. The existence of a feasible assembly sequence confirms the reliability of the body for the product. The assembly of the industrial limit switch consists of several steps, Figure 2.

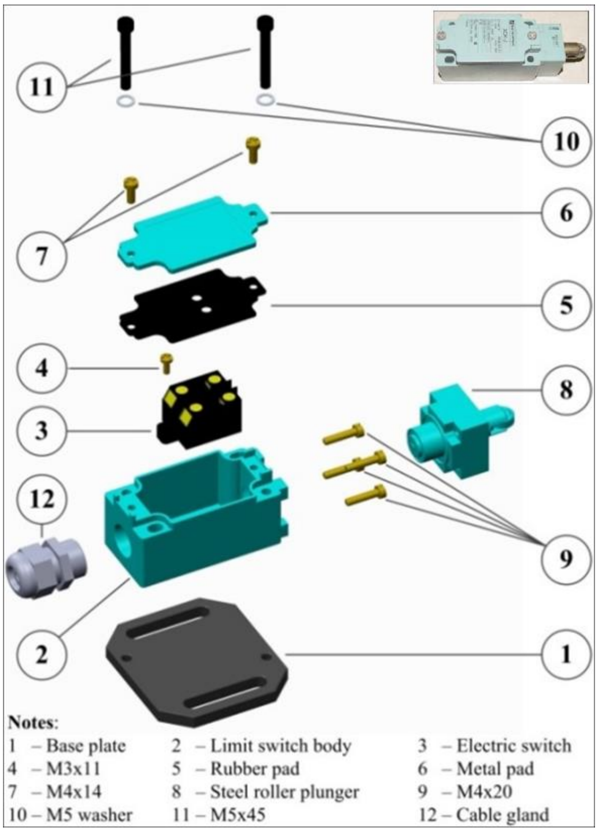


Figure 2. Assembly sequence of the product

Process simulation allows you to design and simulate complex production zones that are in a shared workspace. Synchronization of robotic zones using simulation tools simplifies processes such as evaluating cyclic events and the control emulator of a specific robotic system [Velisek 2017]. Robotics simulation tools allow all robots to design a collision-free operation and optimize their cycle time. In addition to collision detection and prevention, the human model's movement sequence is also evaluating during the simulation for ergonomics purposes (Figure 3).

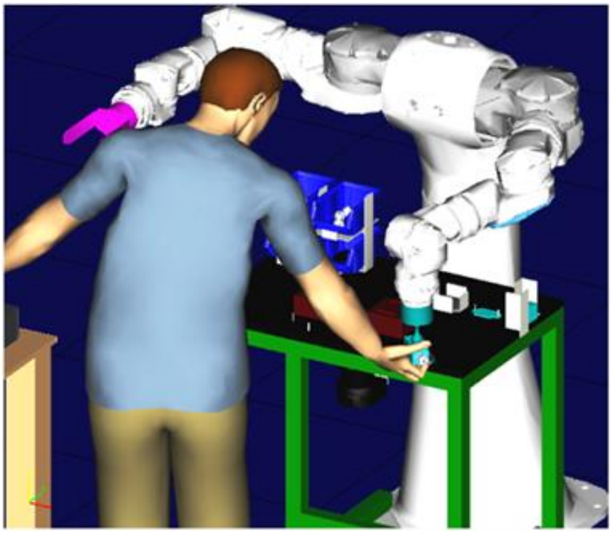


Figure 3. Cooperation between robot and operator during the assembly process

This evaluation principle uses the observation of body postures described by combining all joint positions of the human model. The obtaining of the joint coordinates and motion data is possible through the human simulation. Then follows the evaluation of the resulting load on the human. The motion generated in this way is beneficial, especially for assembly tasks. The combination of standardized motion elements and the calculation of individual body movements reduce the effort required to develop a simulation study.

The human speed (v_h) is variable between *1600mm.s*$^{-1}$ to *2000mm.s*$^{-1}$. For greater safety, the maximum speed of human movement ($v_h = 2000mm.s^{-1}$) and the maximum velocity of the robotic system ($v_r = 250mm.s^{-1}$) are selected based on ISO/TS 13855. The minimum separation distance (Table 1) according to the following equation (2):

Type	Value
human speed	$v_h = 2m/s$
velocity of robotic system	$v_h = 0.25m/s$
the reaction time of the robotic system	$T_r = 0.21s$
time required to stop the robotic system	$T_s = 0.25s$
robotic system stopping distance	$B = 0.0625m$
distance of the operator's body part	$C = 0.9m$

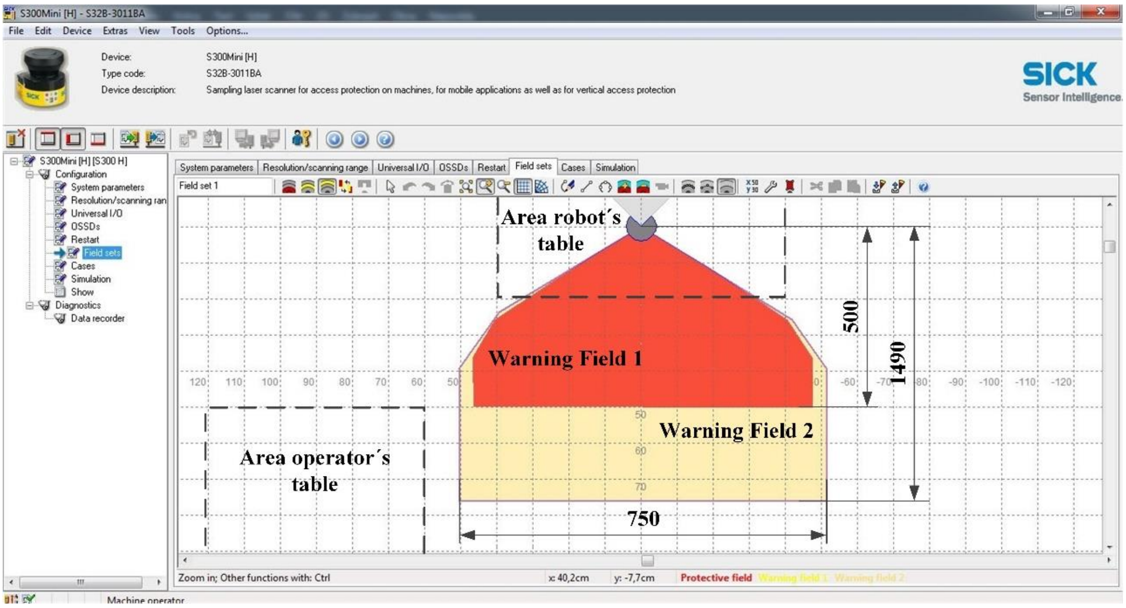
Table 1. Calculation of minimum separation distance

$$S = \big((2 \times 0.41) + (0.25 \times 0.5)\big) + (0.25 \times 0.41) + (0.0625) + (0.9) = 1.49m \tag{9}$$

Using the small 2D laser scanner S300 mini, we monitor three safety zones (one is protective and two are warning) which are programmable using software CDS connected to a computer. The advantage is setting various parameters, such as the zone's shape, the range of scanning zones, the response, and many others (Figure 4).

Figure 4. Location of 2D laser scanner under the workbench within the cooperative workplace

Collaborative safety in the workplace is based on the support and use of the robotic system control functions, specifically "speed Limit" - restriction of robot speed (by warning field 2), Figure 5. The safety also ensures the function "Hold" - suspension of the robotic system - characterized by warning field 1. Outputs of the laser scanner zone use the external digital inputs of the robotic system, according to the available documentation and schemes of the manufacturer.



Device: S300Mini [H]
Type code: S32B-3011BA
Device description: Sampling laser scanner for access protection on machines, for mobile applications as well as for vertical access protection

Figure 5. Proposed 2D laser scanner security zones

Based on the concept of a cooperative workplace, the actual proposal will construct. Workplace requirements consider the mechanical, electrical, and software structure and the implementation of the robot's communication interface [Nemec 2019]. In connection with mechanical construction, some necessary mechanical interfaces are designed and manufactured.

When the distance returns to a length more significant than the calculated distance, the robotic system resumes operation. However, in a shared space where the human and robotic systems work together, it is always necessary to use the most advanced sensors to reduce the risk of injuries.

4 CONCLUSIONS

The application of the collaborative workplace is becoming more and more attractive in the automotive and assembly processes, especially for their advantages that can bring in terms of safety and ergonomics for the operator and quality of the assembled product. In this paper, we test the speed and separation monitoring method (in the context of the ISO/TS 15066) to design and implement a collaborative workplace for assembly purposes. We propose this scenario because of the standard industrial robot participating in the automated workplace. Safety assessment is needed together with considering TS 15066 and functional safety EN 61508.

One of the relevant points for operator safety when working in the same workplace of the robotic system is to ensure that the minimum separation distance is secure in any circumstances. A 2D laser scanner guarantees this from the SICK Company. A linearized formula determines the minimum separation distance between the robotic system and the operator. The minimum allowable separation distance between human and robot is 1.49 meters. If the distance between the robotic system and operator is less than the calculated separation distance, the robotic system will slow down the work. If the operator continues his movement, the robotic system stops immediately. When the length returns to a larger than the calculated distance, the robotic system resumes operation. However, in a shared space where the human and robotic systems work together, it is always necessary to use the most advanced sensors to reduce the risk of injuries.

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