Application of speed and separation monitoring method in human-robot collaboration: industrial case study

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Abstract
Application of human-robot-collaboration techniques in automotive industries has many advantages on productivity, production quality, and workers' ergonomy, however workers' safety aspects play the key role during this collaboration. In this paper, results of the ongoing research about the development of a manufacturing cell for the automotive brake disc assembly that is based on the human-robot collaboration are presented. Operational speed and worker-robot separation monitoring methodology (SSM) as one of the available method to reduce the risk of injury according to the ISO technical specification 15066 on collaborative robot in sharing space with human, has been applied. Virtual environment simulation has been used, considering different percentages of robot maximum speed, to determine the SSM algorithm parameters for estimating the minimum protective distance between the robot and operator. Using ISO/TS 15066 and virtual environment simulation, the minimum separation distance between operator and robot has been estimated. Using human-robot collaboration along with the safety issues specified by SSM system has increased the safety of operation and reduced the operator fatigue during the assembly process.

Key words: *speed and separation monitoring, human-robot collaboration, assembly, worker safety*

1. INTRODUCTION

Nowadays, application of robots in manufacturing industries, especially in assembly lines, has dramatically increased. Many industries such as automotive, airplane and electronic, have been automated up to more than fifty percent although there are still many challenges in implementing this type of automation that are unsolved [1]. In production line, many tasks have repetitive nature such as welding, painting, and handling heavy and fragile objects. The idea of human-robot collaboration is to fill the gap between the manually and fully automated processes. Collaborative robots can be a solution to help an operator while performing the un-complex repetitive tasks. Robots can help the operator to share tasks and increase productivity. Which can lead to improvement of efficient and safe performance [2]. Human-robot collaboration in the same time and space has many hazards and risks related to operator safety. For this purpose, Occupational health and safety organizations rely on national and international standards to provide guidance for maintaining safety in the working environment. The International Organization for Standardization (ISO) Technical Specification (TS) 15066 has listed four different scenarios for increasing safety with industrial collaborative robot [3].

1. SMS: the first method is safety-rated, monitored stop method that requires a software or device to pause the function of robot when the worker is coming closer to the robot in order to prevent dangerous motion.

2. HG: The second is hand guiding method moving robot system by hand-operated device to transmit motion commands.

3. SSM: The third method is speed and separation monitoring which is increasing safety by specifying the minimum protective distance between a robot and an operator in the collaboration work space.

4. PFL: The fourth method is called power force limiting, it allows the contact between on operator and a robot, but the requirement is the control of robot momentum to avoid any injury and pain.

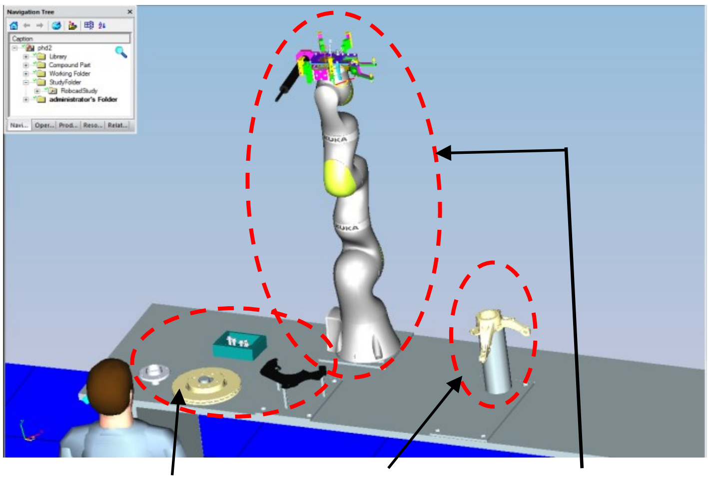
Recently, virtual environment plays an important role in designing various facility of production lines by providing analysis of difficult visualized situation. The implementation of virtual environment helps to reduce the risk of changing the production planning when unexpected dangerous situations are detected; also, it can help to improve cost, process time and process ergonomic safety [4].

The authors of [5] focused on the third method from ISO (TS) to investigate a set of metrics for SSM algorithm and to discover the collision avoidance path based on consideration of safety criteria, sensor uncertainty and variable control factors in robots. The aim of the research activity described in [6] is to present a new method for designing and optimizing hybrid reconfigurable systems. The reconfigurability is addressed by a clear task decomposition between robots and operators. Virtual environment simulation has been used to consider different scenarios of reconfigurability in working station to enhance the operator awareness and reduce the risk of injuries. In the research reported in [7] authors applied virtual environment to implement manufacturing tasks for building aerospace composite parts. This paper has two goals, one of them is short-term goal which is to enhance the behavior of human while collaborating with robot inside the virtual environment. The second goal is long-term goal, they investigated how to improve acceptability of Human-Robot collaboration (H-R-C) and to improve relevant collaborative conditions by means of virtual environment. The aim of the research reported in [8] is to obtain a collaborative procedure that results to be more fluent and acceptable for humans in case of teamwork with robot. The obtained results show an improved collaboration between human and robot and a reduction of stop-and-go command during collaboration. For this purpose, firstly they simulated the collaborative environment with robot and human then tested for confirmation in real world (laboratory environment). They use the virtual environment and train the operator how to behave with robot.

There are many commercial codes available to simulate the manufacturing production line but the most popular one is Tecnomatix which is developed by Siemens company. This code is divided into different segments to design and complete tasks. The segment of Plant Simulation software is aimed to create digital models of production lines and to investigate different potential scenarios for system layouts. The duty of JACK software is to analyze the ergonomic effects on human; another segment is used for programming robots, manufacturing process and analyzing the product assembly process is called Process Simulate software. In this paper Process Simulate segment has been used to simulate the process of the brake disk assembly.
In this research, SSM system along with the virtual environment simulation have been applied to determine the minimum separation distance of human and robot in the brake disc assembly work station.

2. SIMULATION PROCEDURE

In the production line, the assembly of brake disk is performed in several steps. The objective of this study is to reproduce a workbench assembly in one cell, at a laboratory scale, where the human-robot collaboration is introduced. It should be clear that when a human operator and a robot are working together in the same work place, the risk of collision between them is high if not appropriately controlled. In any case is higher with respect to the usual organization where human operator and robot are not working together in the same work place. Therefore, these models allow us to make experience of this relatively new manufacturing environment and further to develop some optimization. The assembly area is divided in two main parts as shown in Fig 1.
(a) Picking area: the zone of the workbench in which the robot picks up the various components for the assembly.
(b) Assembly Area: where the upright and bearing are placed and fixed to allow the assembly.
The complete task on the workbench is subdivided between an operator and a robot as shown in Fig 1. The components to be assembled are placed on the workbench to supply what is needed to perform the assembly tasks and the appropriate tools for the operator. The components located on the workbench consist of the screw kits, the hub kit, the dust protection kit, the brake disc kit and the tip kits.
In order to develop a solution that is acceptable for this human-robot collaboration procedure, which has always a high risk of risk of collision, a kuka robot has been considered in this research. The Kuka lbr iiwa robot has the capability of working with an operator, simultaneously performing multiple tasks. Moreover and importantly in the collision avoidance perspective, this robot has a quick response in the case of dangerous situations. The Kuka (LBR IIWA R820 14”) robot, as illustrated in Fig.1 (c), is used. This robot is characterized by a maximum range of 820 mm and a payload of 14 kg. The name LBR stands for "Leichtbauroboter" that means lightweight robot with 7 degrees of freedom. It is located in front of the workbench. This robot has precise system of sensors placed on each axis.



(a) Picking Area (b) Assembly Area (c) KUKA robot
Figure 1. Workbench area

The aim of applying H-R-C in this procedure is to help the human operator by applying a robot for improving the ergonomic by reducing the workload. This aim is relevant since the part weight is high and might cause muscular pain after repetitive tasks. Due to the fact that, during the manual assembly of brake disc, each operator should lift 5 kg brake disc and each operator works 8 hours in one shift, and during this time he

assembles around 160 brake discs, at the end of the day he results to have lift more than 800 kg. Using H-R-C will reduce considerably the burden lifted by an operator, since the heavy loads are now managed by the robot.
Tasks have been allocated to human and robot as following: The assembly job is started with taking the dust protection from picking area by robot and inserting it on the upright and bearing on the assembly area. Then the 3 M6 screws are taken from the screw kit in picking area by the operator and are tightened on the plate by the robot. In the third step, hub is taken from picking area by the operator then inserted on the dust protection. In the fourth step, the brake disc is picked from picking area and inserted on the hub in the assembly area by the robot. In the last step 2 screws are taken by the operator from screw kit then the robot tights on the brake disc in the assembly area. It is also important to mention that, safety cameras are placed in workstation to detect any kind of human and robot motions during their interactions.
These activities have been reproduced in Process Simulate. In the following lines, it will be described how to use and import the models into the Process Simulate. The parts are subdivided in two categories in virtual environment: The first category is related to those parts without any movement called static link, in other words they are stationary parts like; screw, brake disk, hub, dust protection as shown in Fig 2. The second category contains the dynamic parts, i.e. those parts that have movements such as gripper, robot,…,etc. Process Simulate works just with COJT format, and the only format that can be converted to COJT is JT format, it is necessary to produce parts in JT format in CATIA or NX in the first step.

1.Snap Ring
2. Bearing
3. Up-Right
4. Dust protection
5. Screws for dust protection (3*M6)
6. Hub
7. Screw for brake disk (2*M8)
8. Break disk

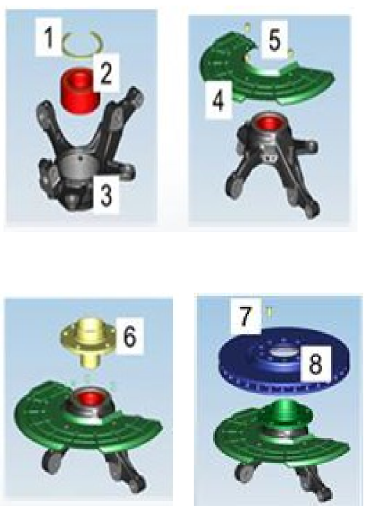


Figure 2: CAD part in NX software

3. SPEED AND SEPARATION MONITORING METHOD

This paper focuses on the third human-robot collaborative scenario: “speed and separation monitoring” (SSM). In order to preserve a static safe separation distance between the robot and a human walking around the collaborative workspace, the SSM method offers a reasonable solution. The purpose of this method is to measure continuously the separation distance between the robot and the operator and compare with the so called authorized (worker protective) distance. Using the SSM method when the separation distance tends to reduce below the authorized distance, the robot stops any kind of motion. The robot initiates again its movement when the separation distance becomes equal or greater than the authorized distance [3,9]. SSM can offer reasonable solutions in order to preserve a safe separation distance between the robot and a human walking around the collaborative workspace. SSM can be implemented both under static and dynamic conditions. The Static SSM method considers constant the human and the robot speeds. While the dynamic SSM method can consider variable speeds. In this research, the static SSM method has been used to reduce potential risks in human-robot collaboration. The equation for calculating the minimum protective distance in human-robot collaboration in ISO/TS 15066 [3] is the extended version of the one which is defined in ISO 13855 [10] for determining the protective distance for immobile machines.
According to the ISO/TS15066 [3], the minimum protective distance, (S), at time (t_0) is given by equation (1).

$$S(t_0) \geq \left(\int_{\tau=t_0}^{\tau=t_0+T_R+T_S} v_H(\tau)dt \right) + \left(\int_{\tau=t_0}^{\tau=t_0+T_R} v_R(\tau)dt \right) + \left(\int_{\tau=t_0+t_R}^{\tau=t_0+T_R+T_S} v_S(\tau)dt \right) + \left(C + Z_S + Z_R \right) \quad (1)$$

Where (V_R) is speed of the robot in the direction of the human, (V_H) is the directed speed of human in the collaborative workspace in the direction of the moving part of the robot, (V_S) is the speed of robot in the stopping path, from activation of the stop command until the robot has stopped. (T_S) is the time to stop the robot motion. (T_R) is the robot responding time in case of the operator presence. Where the part of body can intrude into the sensing area before it is detected, the uncertainty disturbance of boundary distance to exception of operator reach is (C). The uncertainty of robot position and operator position (sensor) are respectively (Z_R) and (Z_S) [3,9].
It is important to mention that, V_R is the robot gripper velocity and (V_H) is the manikin center velocity. The SSM stopping diagram is presented in Fig 3. The total time for stopping the motion of the robot is the summation of the sensor detection time (t_d), the robot reaction time (t_r) and the robot stopping time (t_s). The hazard area is therefore representative of the authorized stopping distance. As soon as the authorized stopping distance is calculated, a stop signal will be sent to the robot control system [11].

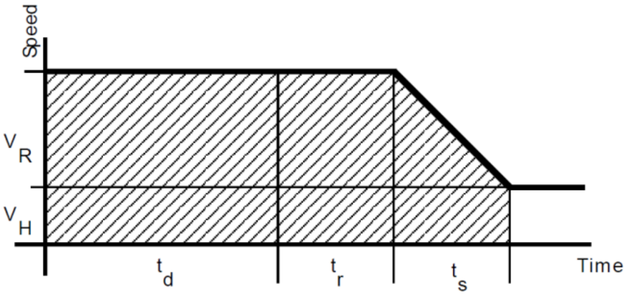


Figure .3. SSM Stopping Diagram [10].

4. RESULTS AND DISCUSSION

Tecnomatix Process Simulate software presents simulation results in two modes as illustrated in Fig 4. and Fig 5.: (a) time-based simulation and (b) event-based simulation. Typically, time-based simulation consists of resources, products and operations whereas for event-based simulation signals should be defined. In time-based simulation, the sequence of operation and period of time process should be defined. In time-based simulation, it is essential to define the kinematic motion for non-stationary parts during the compose of manufacturing process. The main difference between time-based and event-based is that, in event-based simulation the logic box is constructed based on the operations sequence. This means that, this method uses the signal-based logic to define the sequence of operations, in this paper event-based method is used.

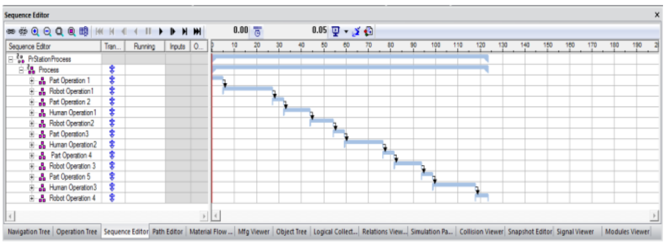


Figure 4. Gantt chart of operations in time based mode

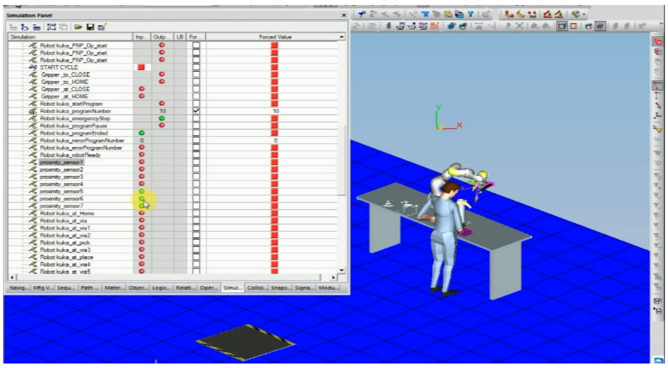


Figure 5. Virtual environment in event-based mode

Equation (2), which is a linearized form of the equation (1), has been used to calculate the minimum allowable robot-human distance under static condition [9,11].

$$S = (V_H T_R + V_H T_S) + (V_R T_R) + B + C \qquad (2)$$

In order to calculate the minimum separation distance, all the necessary factors should be determined. The human speed (V_H) is variable between 1600 mm/s to 2000 mm/s., In order to be on the safer side, the worst-case value of human speed (V_H = 2000 mm/s) is selected based on ISO/TS 13855 [10] and the maximum velocity of Kuka robot (V_R= 250mm/s) is considered. The term (B) which is the robot stopping distance and the term (T_S) are calculated based on equations (3) and (4) respectively mentioned in ISO 10218-1 [12] as following:

$$B = V_R^2 / 2a \qquad (3)$$

$$T_S = V_R / a \qquad (4)$$

In the equations (3) and (4), (a) is the worst-case deceleration value of the robot during the stopping procedure.

While equations (2)-(4) seem to be simple, a quite complex procedure should be done to determine these values. The two parameters (T_R) and (a) should be determined through the simulation procedure and the formula presented by [3]. According to [9] the stopped position of the robot ($P_{s,i}$), which is the summation of robot distance traveled while the sensors are detecting plus the distance traveled while the robot stopping begins, is calculated for different percentages (i%) of robot maximum velocity (V_R) as following :

$$P_{s,i} = (V_{R,100}T_R + \frac{V_{R,100}^2}{2a} + P_{s,100}) - (V_{R,100}T_R)i - (\frac{V_{R,100}^2}{2a})i^2 \qquad (5)$$

Having determined the stopping position of robot regarding to different percentages of robot maximum speed through the simulation, it is possible to implement the regression analysis in equation (5) to determine the values of the variables of (T_R) and (a). Then the robot stopping distance and stopping time (T_S) can be easily calculated based on equation (3) and (4). However, to calculate (C), which is the summation of robot and human position uncertainty and intrusion distance safety margin for separation, is a quite challenging process. One way to calculate (C) based on ISO 13855 [10] is throughout consideration of the worst-case scenario, which is implemented in this research following what reported in [3,9]. According to the above-mentioned description, the parameters of equation (2) are determined as in Table 1. The minimum separation distance is calculated as below:

Table 1. Parameters of minimum separation distance equation

V_H = 2 m/s
V_R = 0.25 m/s
T_R= 0.41 s
T_S = 0.5 s
B = 0.0625 m
C = 0.9 m

$$S = ((2*0.41) + (0.25*0.5)) + (0.25*0.41) + (0.0625) + (0.9) = 2m$$

The schematic of human-robot interaction in the assembly cell is shown in the Fig 7.

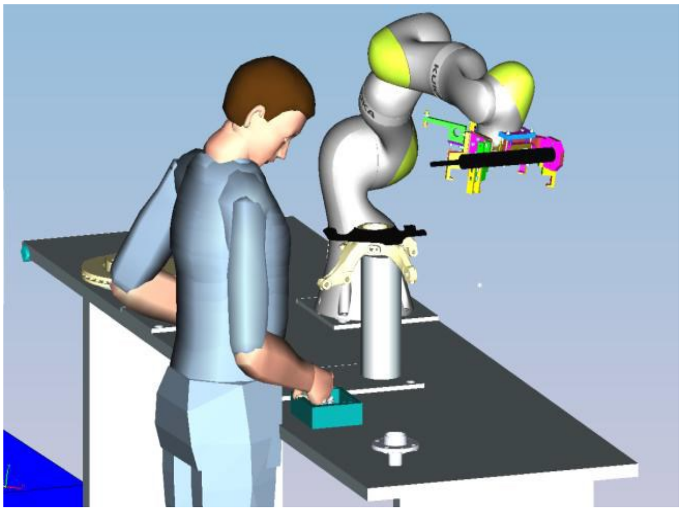


Figure 7. Human-Robot collaboration in assembly cell

Sensors in the working area calculate the distance (D) between the robot and any moving or movable object all the time as soon as (D) becomes less than the minimum separation distance (S). Sensors will issue a stop signal to the robot and the robot stops any kind of motion as shown in Figs 8., and 9.; again, when (D) becomes larger than the minimum authorized distance the robot begins to work.

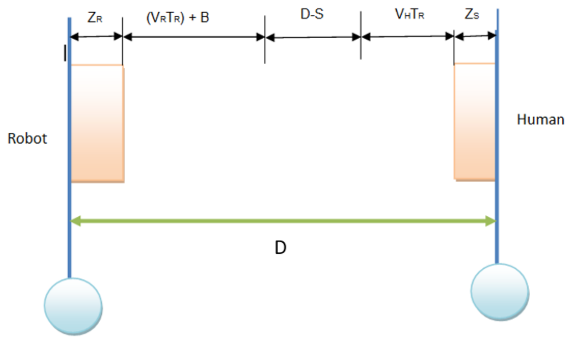


Figure 8. The SSM issues a stop when (D – S) < 0 [10]

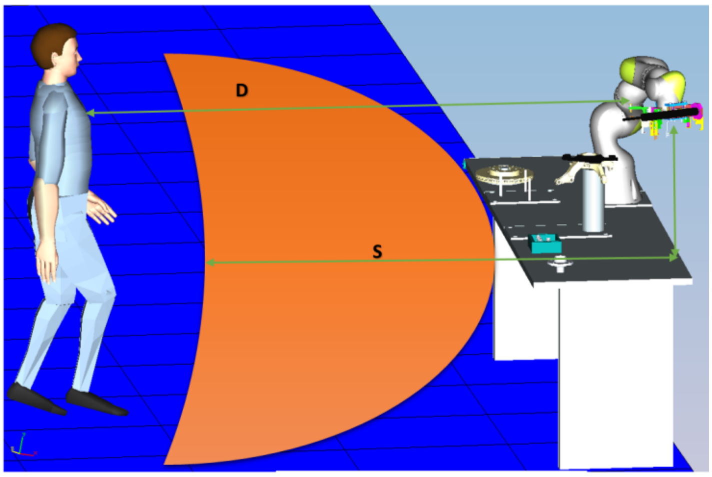


Figure 9. Human-Robot collaboration with SSM method

5. CONCLUSIONS

The application of the Human- Robot Collaboration is becoming more and more interesting in the manufacturing industry and in particular in the automotive plants, for the advantages that can come in terms of safety and ergonomic issues for the workers and in terms of quality for the products.

In this paper, SSM system, as one of the available evaluation procedure in ISO/TS 15066, has been applied to increases safety in assembly cell using human-robot collaboration.

One of the relevant point for worker safety, when he is working in the same workplace of the robot, is to assure in any circumstances that the minimum separation distance is maintained.

According to the ISO/TS 15066, a linearized formula has been used to determine the minimum separation distance between the robot and human in assembly work station. In order to determine the parameters, necessary to estimate the robot stopping distance (B), robot stopping time (T_S) and human-robot position uncertainties (C), a virtual environment tool has been used to simulate the assembly process through different percentages of robot maximum speed with respect to different stopping position of robot. The minimum allowable separation distance between human and robot has been calculated as 2 meters. As soon as the distance between the robot and human becomes less than the authorized separation distance, the robot stops working and when the distance returns to be larger than that the authorized one, again the robot begins to work.

However always there is a need to use the most advanced sensors in the working area where human-robot cooperation takes place in order to reduce any risk of injuries.

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