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# Management of Laser-Cut Sheet-Metal Part Using Collaborative Robots

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**Abstract.** Small-medium enterprises (SME) specialized in laser cutting and sheet metal working area join the Industry 4.0 (I4.0) revolution in order to preserve their competitiveness in the global market. This study aims to integrate new I4.0 enabling technologies into the design and implementation of the laser cutting process for sheet metal parts in order to improve the working conditions of the operators, enhance the product quality, and increase the SME's productivity. The paper proposes a human-robot collaborative workspace for the detaching, removing, and disposing of the metal sheet parts after laser cut.

Such activity is typically performed by human operators because it is difficult to automate. Moreover, such activity is always tedious, sometimes dangerous, and often it is ergonomically heavy.

The paper presents a new approach using collaborative robots for the management of sheet metal cut parts, specifically for developing the removing and sorting tasks of the cut sheet metal parts from the blank skeleton. The proposed solution integrates both the design tools, specifically the CAD/CAM environment where the sheet metal parts are modeled and the laser cutting process is defined, and the production tools, which are the Cobots automatically programmed to carry out the sheet metal parts removal. The study proposes both a simulated solution and real case applications.

**Keywords:** Cobots, human robot collaboration, laser-cut sheet metal removal.

## 1 Introduction

SME specialized in sheet metal working are approaching a revolution by following an I4.0 path. The main objective of this trend is to integrate new enabling technologies to improve working conditions and increase the productivity and product quality of the SME. Obviously, the main aim is not to eliminate human intervention for financial purposes only, but mainly to optimize the production process and improve the ergonomics of the human operator workcell.

The integration of a collaborative robot (cobot) into the working station, where the human operator performs detaching, removing, and disposing of the metal sheet parts after laser-cut, could improve ergonomics of the working condition, shorten the process time of the operator and reduce repetitive tasks of the human operator.

Automation of detaching, removing, and sorting processes of the metal sheet parts after laser-cut can lead to increased productivity and flexibility and reduced setup and tooling costs. Possible automated solutions for loading/unloading processes and for detaching activities metal sheet parts after laser cut are provided by the TRUMPF company [10]. However, existing solutions do not consider human operator interventions. Cobots are one of the enabling tools of the I4.0 [1]. The cobots have a compact shape, they occupy not so much space and can be easily collocated in different positions, rather than a traditional industrial robot. There are not safety barriers around them, because in terms of safety they are provided with some sensors that can immediately and automatically stop the robot if they detect some obstructions or errors.

Human Robot Collaboration (HRC) is a form of interaction between human and robot. In the HRC environment, cobots are intended for direct human-robot interaction, within a shared space of the workplace, or where human and robot are in close proximity. This kind of environment is then more inclined to a combination of human skills and robot skills and the scientific literature provides numerous researches and interesting results. Authors already analyzed the applicability of the human-robot interaction in SME and the evaluation of the ergonomic risks of the worker during the detaching process using ergonomic assessment worksheet (EAWS) tool [2].

Other researchers proposed an automatic framework for designing the human-robot physical interaction [3]. The operator programs a collaborative robot by demonstrating a task and the robot autonomously performs pick and place repetitive movements after a number of demonstrations. Such research has been demonstrated with a prototype at the laboratory level but its implementation in a real manufacturing scenario is still pending.

To evaluate HRC workstation in different profiles conceptual evaluation framework is proposed by authors [4]. The integration methodologies of cobots to the human workspace to perform collaborative tasks with a human operator in an assembly workcell are proposed by [5, 6]. HRC manufacturing assembly cell is designed and developed in [7]. They proposed a task model approach to plan the collaboration and task execution based on human considerations. HRC prototype system is evaluated for five safety designs and risk assessment is conducted to verify the safety design.

The authors of [8] claim that it is possible to implement and design HRC workcell through lean thinking approach. The proposed methodology is adopted using industrial case studies that are focused on the steps of the HRC design process such as task allocation and scheduling.

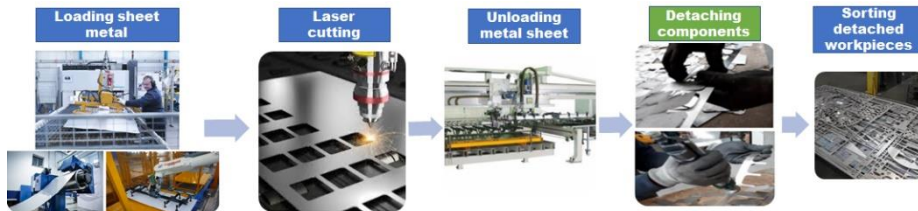
In contrast to the above mentioned papers, this research provides a design and integration methodology of cobots to the human operator workcell where a worker performs the detaching, removing and sorting activities for the cut sheet metal parts. Moreover, in a newly designed human-robot workcell, a human operator can perform all tasks through the use of a cobot (UR3) automatically or in collaboration. The study demonstrates the integration of real and simulated tools to the designed human-robot workspace environment. Designed human-robot workstation receives CAD/CAM model from laser cutting machine with all specifications of the laser cutting process of metal sheet. Afterward, in the human robot workstation, a cobot with a special gripper performs detaching of the workpiece components.

The paper is organized as follows: first sheet metal laser cutting process flow is described, then the proposal of the human-robot collaborative workstation to detach metal parts is presented, and finally simulated and real case framework of the automated detaching system and results are discussed.

## 2 Sheet Metal Laser Cutting Process

The integration of I4.0 technologies and, specifically, the introduction of robotics for the automation of sheet metal laser cutting lines, requires a deep knowledge of the production process.

The laser cutting process in SME is mainly composed of five phases that are roughly illustrated in figure 1.



**Fig. 1.** Laser cutting sheet metal process flow

*Loading sheet metal* is the first procedure of the laser cutting process as illustrated in figure 1. The manual sheet metal loading can be carried out by human operators, but completely automated loading systems are commonly available in laser cut workstations by integrating an automated loading machine and the laser cutting machine. The utilization of industrial robots allows for the appropriate level of flexibility and productivity in sheet metal loading thanks to the reconfiguration of industrial robot tasks.

In the manual loading mode, one or two operators feed the laser cutting machine by putting one sheet metal on the laser machine bed, which is then moved to the laser cutting area.

In the automated loading mode, the metal sheets are stored in a stocking area and an automated system gets the sheet metal and moves it to the laser cutting area.

*Laser cutting.* Once the localized heating, melting or vaporizing has started, the machine moves to the area of material removal across the workpiece to produce the full cut. The machine performs the movement either by adjusting the reflective mirrors, controlling the laser cutting head, or manipulating the workpiece. There are three different configurations for laser cutting machines, according to the laser beam control system: moving material, flying optics, and hybrid laser cutting systems.

- *Moving Material.* Moving material laser cutting machines feature a stationary laser beam and a movable cutting surface. The workpiece moves mechanically around the

fixed beam to create the necessary cuts. This configuration allows for uniform and consistent standoff distance and requires fewer optical components.

- *Flying Optics*. Flying optics laser cutting machines feature a movable laser cutter head and a stationary workpiece. The cutting head moves the beam across the stationary workpiece in the X and Y axes to produce the necessary cuts. The flexibility of flying optics machines is suitable for cutting materials with variable thickness and sizes, as well as allowing for faster processing times. However, since the beam is continually moving, the changing beam length throughout the process must be considered. Collimation (alignment of the optics) can control the changing beam length, using a constant beam length axis. Adaptive optics or capacitive height control systems are capable of making the necessary adjustments in real-time. This system is the most common one.
- *Hybrid*. Hybrid laser cutting machines offer a combination of the attributes found on moving material and flying optics machines. These machines feature a material handling table that moves on one axis (usually the X-axis) and a laser head that moves on another (usually the Y-axis). Hybrid systems allow for more consistent beam delivery and reduced power loss. Hybrid systems have greater capacity per watt compared to flying optics systems.

*Unloading sheet metal*. As for the loading case, this operation could be done manually or automatically. In figure 1, an automated machine that performs both the operations (loading and unloading metal sheets) is presented as an example. Nevertheless, the unloading process is more complex than the loading process because of the number of different parts embedded into the sheet metal and their sorting and storing.

*Detaching components*. Detaching process changes according to the presence or absence of micro-joints. The micro-joint is a small uncut area that links the cut part to the blank. The micro-joint prevents the detaching of the cut part from the blank and it facilitates the transportation of the laser cut sheet metal but makes the detaching of the laser-cut parts more difficult. Only the detaching of some reasonable large cross sectional components without micro-joints are automated while the other situations are usually performed manually or with detaching instruments.

*Sorting*. Sorting is directly linked with the detaching process. After detaching process human operator sorts detached components into the boxes. A manual sorting process performed by the operator is not ergonomically comfortable and automation of detaching process gives the possibility directly automate sorting process as well.

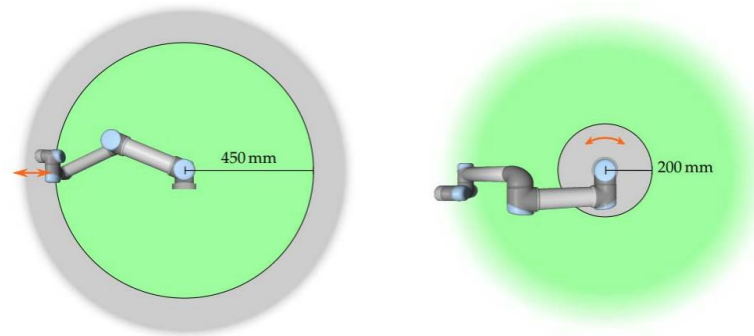
In the next chapter, we focused to develop a human-robot workstation to investigate different ways of detaching process and sorting processes of laser cut pieces since it can be ergonomically improved by integrating enabling technologies of I4.0.

### **3 Development of Human-Robot Workstation Design**

A human-robot workstation has been designed Politecnico di Torino (POLITO) using tools and technologies available at the Laboratory of Economics and Production (LEP). The proposed workstation comprehends a collaborative robot from Universal

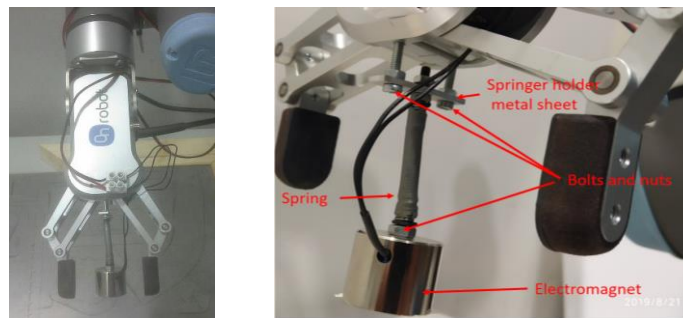
Robots (UR3), an electromagnetic gripper, a laser-cut sheet metal with dimensions 500x500 mm, and stocking boxes.

*Collaborative robot UR3* belongs to the CB series with capabilities of a 3 kg payload and a 500 mm extension range from its base. There are other products from Universal Robot that allow more payload and extension due to a more robust mechanical structure (UR5, UR10). UR3 is a 6-axis robotic arm and its workspace is spherical. To identify reachable components it is important to investigate the working area of UR3, which ranges from the 200 mm radius to the 450 mm radius around the robot base, as illustrated in Figure 2. If the workpiece is located in the unreachable zone the robot arm cannot reach the target workpiece and the removal process fails.



**Fig. 2.** UR3 working range [9].

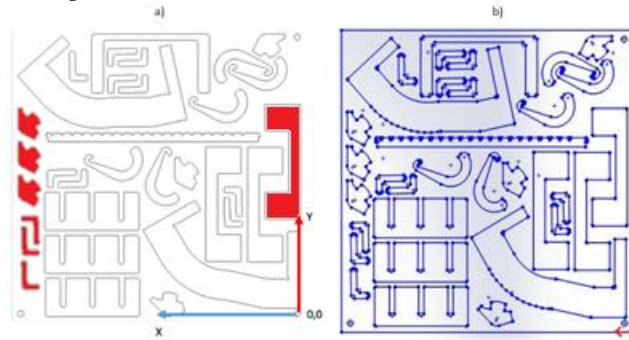
*Electromagnet gripper.* In order to perform grasping action on the surface of the metal components and to perform detaching actions to remove workpiece components from the metal sheet, a gripper to grasp metal components is required. For the proposed collaborative workstation, we developed an electromagnet gripper as shown in figure 3. The electromagnet gripper can be mounted to the existing mechanical gripper RG2 from OnRobot that is installed on the UR3.



**Fig. 3.** Mounted electromagnet gripper to the end effector of the UR3.

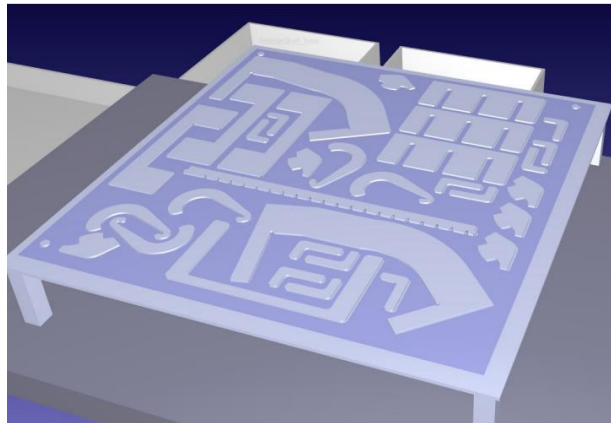
*The laser cut metal sheet* has a square geometry with dimensions 500 x 500 mm. There are 7 different shapes for 33 elements in total, but only 27 of these elements will be

detached and removed from the blank skeleton and put in the corresponding boxes. In figure 4(a) detachable metal sheet parts are colored with white and not reachable parts are colored with red color. Figure 4(b) shows all components on the CAD file, red arrows are reference points of the sheet metal.



**Fig. 4.** Laser cut metal sheet: a) not detachable parts are colored with red color; b) CAD view of the metal sheet

In order to place the metal sheet into the working area of the collaborative robot after the laser cutting process a *supporting system*, shown in figure 5, is required. The support system is located in the working area of the UR3. The dimensions of the supporting system are 500x500x45 mm. The supporting system is made of aluminum profiles with 90° connectors and special bolts to fix the assembled support.

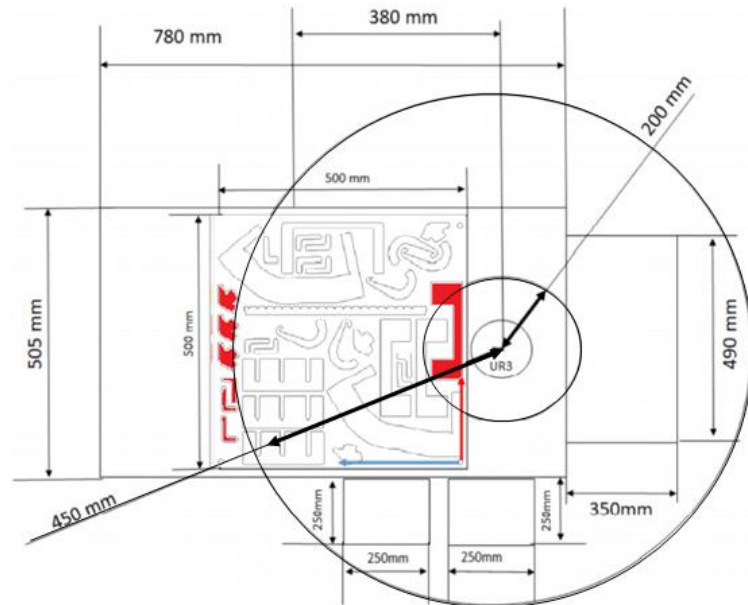


**Fig. 5.** Supporting system to place sheet metal.

For the sorting processes of the detached components, different *stocking boxes* are designed and integrated into the workspace of the UR3. The stocking boxes serve to store the detached components after the detaching operation. UR3 makes sorting and ordering by placing the components into the boxes.

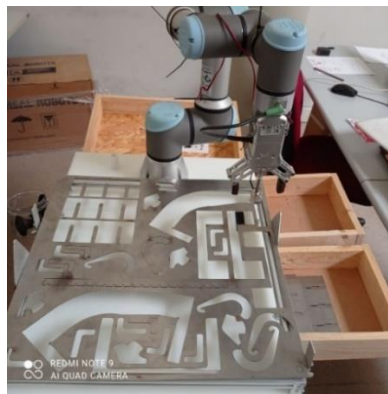


Figure 6 depicts 2D drawings of the human-robot workstation with UR3 reachable area to detach laser cut parts. On the right and downside of the workcell, stocking boxes are located for sorting and placing the detached components.



**Fig. 6.** UR3 with the reachable area and metal sheet on the human-robot workcell.

Figure 7 illustrates a real case human-robot collaborative workstation with all components. The workcell has a supporting table that is dedicated to the metal sheets with dimensions 500x500 mm.



**Fig. 7.** Real case workcell with the automated detaching application.

#### **4 Framework of Automated Detaching System for Laser Cut Sheet Metal Parts**

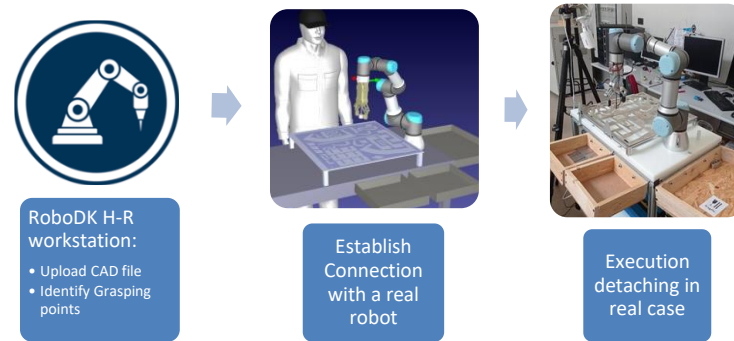
The development of the automated detaching workstation starts with the creation of 3D models for workcell components and their implementation in a simulation environment based on RoboDK software (POLITO has a RoboDK educational license). The simulator gives the possibility to program robots in online and offline modes. The simulation of removal processes requires the identification of the grasping point of each laser cut part available in the sheet metal. Such operation is performed in a CAD environment where the appropriate evaluation of 2D geometry of laser cut parts (mainly center of mass and inertia properties of features in the CAD file) identifies the coordinates of the grasping points. Such coordinates are imported to the RoboDK environment and re-evaluated in order to align the reference frame in the CAD file. The resulting reference frame is located with respect to the UR3 base, thus allowing the identification of the grasping points of the detaching parts according to the reference frame.

The availability of grasping points in the RoboDK simulated environment allows for programming the detaching process of the laser cut sheet metal parts. The simulated detaching process, free of collision and critical situation, can be executed in the real workstation by connecting RoboDK to the UR3 robot using TCP/IP protocol. Such operation compares the simulated process and the real case activity.

The simulation environment manages detaching and removal processes for two different cases: the metal sheet with micro joints and without micro joints.

In both cases, UR3 with electromagnetic gripper moves to the grasping coordinates with respect to the reference frame. Once UR3 reaches the target positions, an electromagnet is activated using digital output (DO[0]) and the gripper attaches the workpiece to the surface of the electromagnet gripper. After detaching the workpiece from the initial positions UR3 with electromagnet gripper places detached workpieces to the indicated boxes according to the size of the boxes and workpieces. The robot detaches the components from the metal sheet until it removes all the reachable components in the metal sheet.

Figure 8 demonstrates the steps for the development of an automated detaching system for laser cut sheet metal parts.



**Fig. 8.** Proposed framework of automated detaching system for laser cutting sheet metal parts

The default simulation speed is five times faster than in real-time but the ratio can be changed in the simulation environment. When the laser cut sheet metal parts do not have micro-joints, the identification of the grasping point allows for the programming of automated removal and storing process. The UR robot moves the electromagnet to the grasping point, activates the magnetic field, removes the part from the blank, and moves it to the specified box.

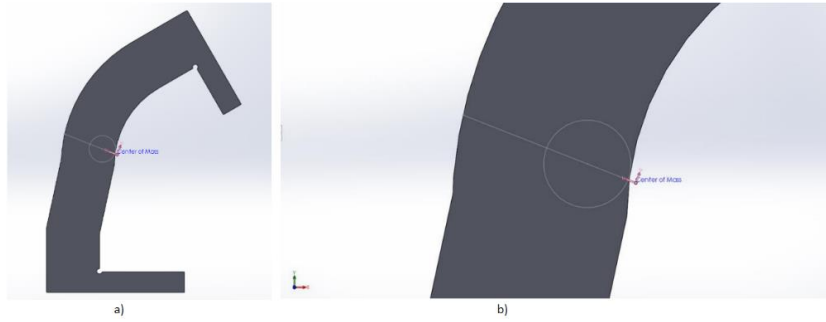
Viceversa, parts with micro-joints require a detachment process that separates the part from the blank. The detachment process applies force and torque that cause a fatigue failure of the micro-junction. All three cases are described and analyzed in the next chapter.

## 5 Case studies

In this chapter three detaching approaches have been analyzed within the three case studies: Case A: cobot only detaching without micro joints; Case B: cobot and human operator detaching with micro-joints; Case C: cobot only detaching with micro-joints. After each detaching operation, according to the size of the elements, sorting and placing into the stocking boxes have been performed as follows: small piece elements have been programmed to be sorted and placed into the box with dimensions 250x250x10mm; medium piece elements into the box with dimensions 250x250x10mm and large pieces into the box with dimensions 350x490x10mm.

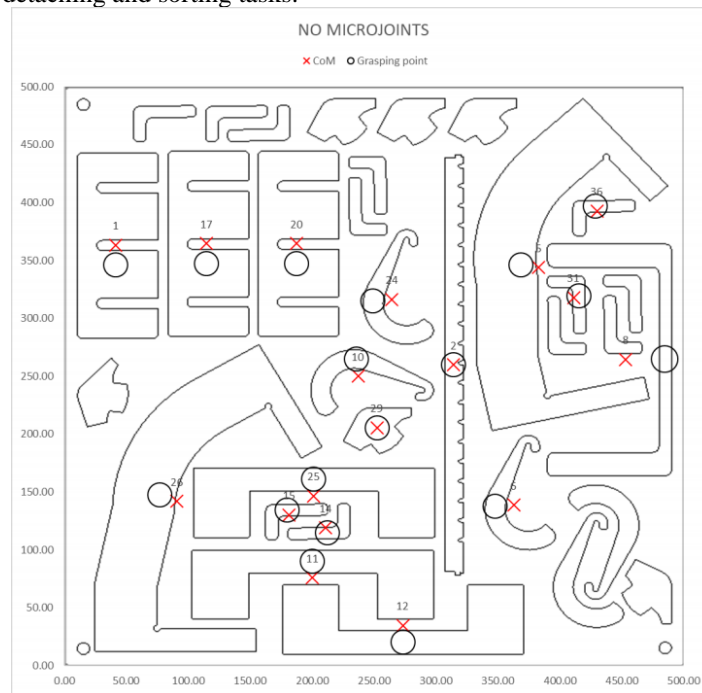
Case A. This case study involves the cobot that picks, detaches and places workpieces attached to the metal sheet with no micro-joints. The main challenge is to evaluate the best grasping point for complex shape pieces since their centre of gravity is outside the cut shape. Normally, for convex shapes, the grasping point coincides with the centre of mass. Contrariwise, the grasping point for the concave shapes is different from the centre of mass (CoM) and it is outside from the cut shape. Figure 9 depicts a convex shape workpiece that has CoM outside the cut shape. For such convex shapes,

the methodology is to recompute grasping points by moving alongside the principal axis of inertia, to minimize the torque generated due to the mass of the component itself.



**Fig. 9.** Convex shape workpiece: a) Center of mass outside the cut shape b) enlarged view

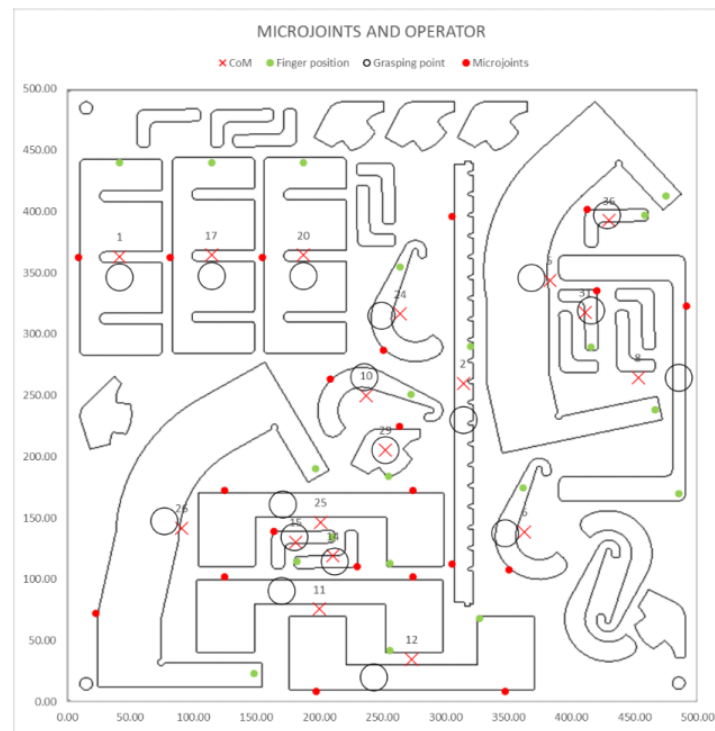
Figure 10 shows CoM (indicated with red “x” sign) and recomputed grasping points (indicated with the circular shape) of the workpieces on the meal sheet. Thus, in this case, cobot receives all grasping points computed on the RoboDK and executes pick and place, detaching and sorting tasks.



**Fig. 10.** Grasping points respect to the CoM

Case B. In the case of B, workpieces have micro-joints, detaching process of the workpieces involves a human operator who collaborates with a robot. In this process,

the new grasping points have been calculated with the aim to allow enough space for the operator to push with the finger, thus generating a torque that is used to detach the components. Once the pieces have been detached by the operator, the cobot using a magnetic gripper has to move detached workpieces to the boxes. Figure 11 demonstrates CoM, micro-joints positions and, recalculated grasping points of the cobot and, proposed finger positions for the operator to apply a force.



**Fig. 11.** Grasping points of the cobot, finger positions of the operator when there are micro-joints on the workpieces.

Case C. Case study C does not involve the operator and the cobot must detach autonomously the pieces attached to the metal sheet by means of the micro-joints. The new set of grasping points has been computed with the aim to maximize the lever arm of the force applied by the electromagnetic gripper with respect to the micro-joint. An oscillatory force is then applied to develop the necessary momentum to break the micro-joint. Figure 12 shows recalculated cobot grasping positions of the workpieces when there are micro-joints. The grasping points have been moved to increase the lever arm and thus the ability to generate a larger torque.

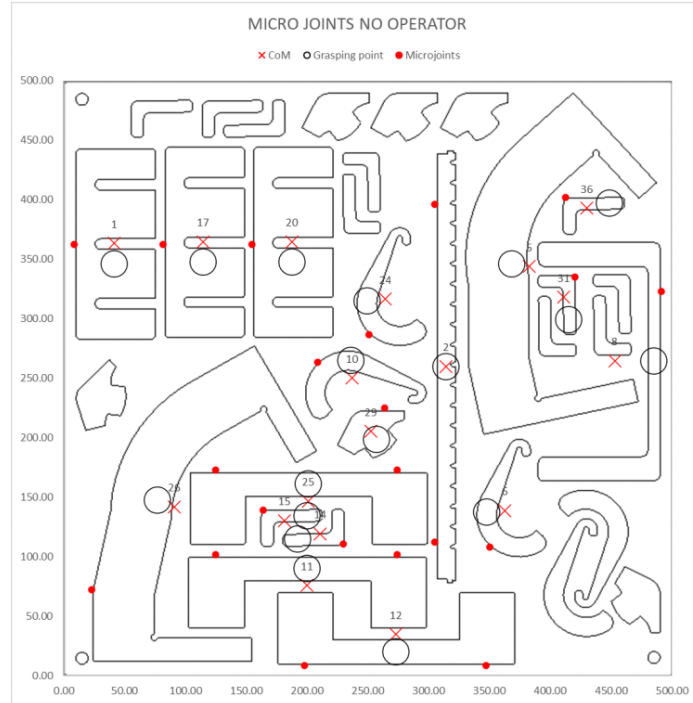


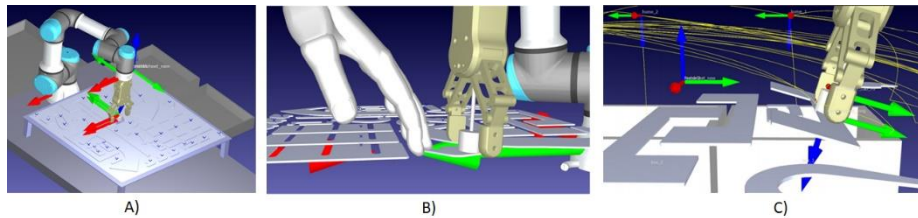
Fig. 12. Grasping points with micro-joints without human collaboration.

## 6 Results and Discussion

This chapter discusses the results of the three cases of detaching workpieces from the metal sheet after a laser cut. The detaching process was tested in simulation and real case environment that gave the possibility to simulate a workstation and to evaluate the system in real-time through online programming using a collaborative robot and human operator. First, a simulation environment of the workstation has been created and after that, we used online programming from the simulator to the real case application.

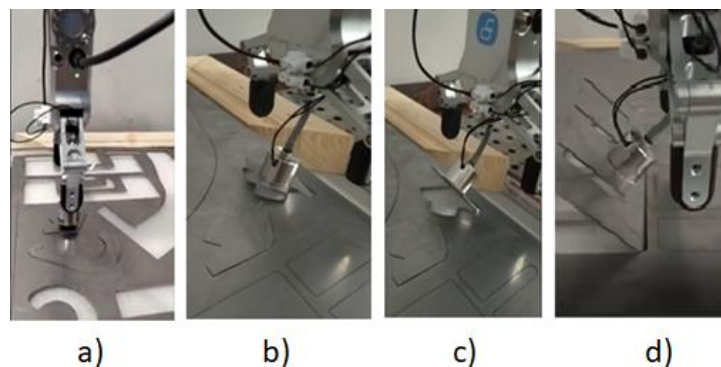
In the simulation, grasping points were extracted from the CAD file of the metal sheet and grasping positions sent to the real cobot using online programming. In the simulation and in a real case situation, the reference frame of the metal sheet was placed using a user-defined reference frame that was with respect to the base of the UR3 that helped to find workpiece coordinates on the metal sheet.

In figure 13, the simulation results of the three case studies are demonstrated: A) Case A simulation of the workstation where cobot is detaching workpieces without micro-joints; B) Case B where cobot and human operator arm detaching workpiece with micro-joints, human is applying force and electromagnet gripper is holding the workpiece; C) Case C simulation where cobot is detaching a workpiece with a micro-joint is depicted.



**Fig. 13.** Three case studies simulation results.

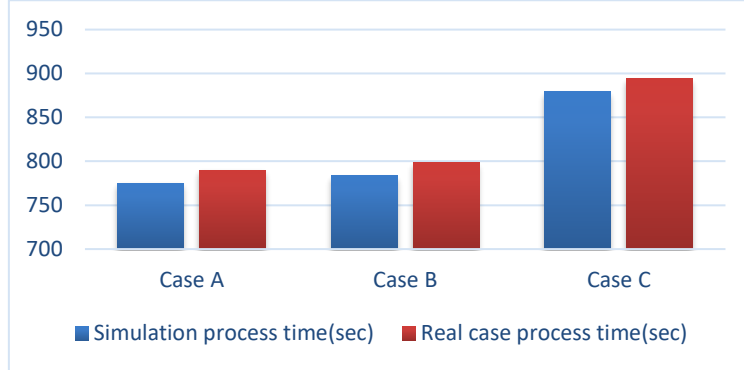
In a real case of detaching processes, all the tools and methodologies are combined. As the tool, we used UR3, electromagnet gripper mounted on the end effector of the UR3, human-robot workcell, aluminum support for metal sheet, boxes to place detached workpieces, and automatic identification of grasping points from CAD file. Figure 13 shows the real-time detaching process of laser cut parts from metal sheet. In figure 13a electromagnet gripper is picking the laser cut piece without micro-joint from metal sheet. Figure 13b, figure 13c, and figure 13d show the electromagnetic gripper detaching process after laser cut sheet metal parts with micro-joints.



**Fig. 14.** Real case detaching process

In figure 15, the real-time and simulation process time differences of three case studies are presented. The processing time of case A, where cobot detached workpieces without micro joints required only 775.4 seconds in simulation and 790 seconds in a real case. For detaching process in case B where cobot and human operator arm detached workpieces with micro-joints required 783.7 and 798 seconds respectively in simulation and in real cases. Finally, case C required more time to detach the workpieces from sheet metal where simulation process time resulted in 879.2 seconds and

real case processing time was 894 seconds. Case C time consumption was due to oscillatory force applied to develop the necessary momentum to break the micro-joint.



**Fig. 15.** Simulation and real case process time comparison.

This study has several limitations, which must be improved in the future:

- A designed workcell area is considered for the metal sheets with dimensions 500x500 mm. The working area must be increased for large metal sheets.
- The case study has been tested with one type of metal sheet. It should be tested with different shape parts and different dimensioned metal sheets.
- The study design has been developed in the laboratory level and lacks integration in the real SME production process.
- Custom electromagnetic gripper is used for detaching process. Other grippers such as air suction or other solutions must be tested.

## 7 Conclusions

This paper demonstrates the applicability of cobot to manage laser cut sheet metal parts within the simulation and real case environment. The developed human-robot collaborative environment is tested in three cases: cobot detaches laser cut metal sheet parts when there are no micro-joints; cobot with a human operator detaching with micro-joint/s; detaching workpieces with micro-joint/s but without cooperation of a human operator and after each task, cobot sorts removed workpieces into the different sized boxes according to their dimensions. The proposed human-robot workcell within the implemented enabling I4.0 technologies can improve the ergonomics of the human operator working station and increase the productivity of the SME. Moreover, such workcell can save the operators time from monotonous tasks. Integrated cobots can handle tasks that require more precision and repeatability and the task distribution between human and robot can reduce stressful activities that affect the wellness of the workers.



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