A Semi-Automated Welding Station Exploiting Human-Robot Interaction

A SEMI-AUTOMATED WELDING STATION EXPLOITING HUMAN-ROBOT INTERACTION

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ABSTRACT. The paper highlights the set up of a laboratory experiment reproducing a semi-automated welding station, for small batch production, with human and robot interacting during the execution of the joining process. Robot training is committed to the human co-worker making use of the Programming by Demonstration (PbD) method. The aim of the experiment is to demonstrate that PbD is exploitable even in a factory environment using ordinary industrial robots. The training of the robot by a teacher (the welder) inexperienced in robot programming, is the key for the introduction of robots in a wide variety of industrial sectors characterized by production in small batches, lack of knowledge about robot programming, lack of convenience in a full automation of the assembly operations. The challenging aspects of the research are the need to satisfy the industrial requirements of high productivity, process accuracy, workers' safety when interacting with robots..

1 INTRODUCTION

Small batch production is generally a sector where automation, moreover robot automation, is seldom employed. This is also the case of the gas metal arc welding (GMAW) process.

There are many reasons behind this statement. A welding station, if operated by human workers, does not require the customization of the tools and fixtures used to fix the parts in the correct position before joining. Furthermore the edges to be welded are not required to have an accurate and repeatable clearance each with the others as they can be adjusted and their surfaces polished and often grinded before welding.

On the contrary, an automated welding station requires specially devoted devices to move and held the parts to be welded. It requires a far more accurate positioning of the parts and sometimes a previous treatment of the surfaces to be welded. A handling machine, or a robot, is required to handle the assembly to and from the workstation.

There are also other and perhaps more compelling motivations behind the scarce diffusion of welding robots in the small productions. There is the need for a skilled robot programmer, in order to teach the welding tasks to the robot and the time required to generate the program and to verify it is usually long compared with the time required by a human operator to manually joining a few work pieces. The robot teaching is performed by simulation on a virtual environment, and by executing pre-production test experiments. During all of this time the welding station cannot be used for production. Large factories usually have offline training stations equipped with the

same robots used in the line. All the robot programming and testing operations can be therefore executed offline without slowing down the production.

Despite all these difficulties, automated robot welding has a number of advantages that makes appealing its adoption. GMAW poses a number of safety problems for the human workers. The electric arc imposes the use of protective gloves. The heat generated during the process is a serious issue and requires the use of protective clothing. The high intensity of the light emitted by the electric arc can cause possible burning of the retina and make the use of protective helmets compelling. The toxicity of the gas used and of the smoke produced during welding is another issue. There is even a risk of explosion for some gases employed in the GMAW [1][2].

Even though training of workers to use GMAW is relatively easy, it is impossible to guarantee a good reproducibility of the welded joint even for a skilled operator. A number of variables are responsible for the weld quality among which position and orientation of the welding gun, rate of movement of the gun, feed rate of the electrode, distance between the contact tip of the gun and the part surface. It is apparent that a robot can execute the operations keeping all of these variable under a more strict control.

The conclusion is that robotic welding is preferable to manual welding but its introduction in small factories faces several difficulties. Starting from this assertion, present research aims at removing the main obstacles to the automation of the GMAW even for small batch production.

The idea is simple but effective. It starts from the observation of several researches dedicated to the automatic learning of complex industrial operations by observation of the same operations executed by a human worker [3][4][5][6]. In present case the robot is trained to execute the welding by the observation of a number of replicated welding executed by a human operator. The acquisition of the human movements is performed by using a motion capture technique, i.e. several cameras observe the movements of many markers conveniently placed on the welding gun and the position and orientation of the gun along the time (trajectory) is hence extracted. The trajectory of the robot in the joint space will be calculated by statistical regression on the basis of the many trajectories just acquired. There are different methods to do this and all of them belong to the research field called "Training by Demonstration" (TbD) [7]. TbD is widely applied in many fields, where robot arms or robotic vehicles are employed. To the author's knowledge, TbD has quite a scarce application in the industrial environments, where the most used programming technique continues to be the playback.

The reason for this is that it is not an easy task the direct conversion of an industrial process, like welding or handling, from manual to automatic execution. It is impossible to directly imitate the human movements during the execution of a production operation. Quoting [8]: "… the transformation of human motions to adequate robot motions is difficult or even impossible, due to kinematic constraints of the robot and the enormous manipulation skills of a human."

In order to introduce TbD in the factory practice it is necessary to define accurately the number and the types of activities the robot has to perform, to build a pre-existing knowledge about some basic movements and to use expert tools to generalize the human movements and to match them with the robot movements library. Additionally the human operator should interact with the robot to execute the tasks not assigned to the robot and to direct the robot movements.

There is the additional necessity of assuring the safety of the human worker that should never be in the reach of the robot when in a working state. This is accomplished by using an advanced laser scanner system to replace physical fences with the concept of safe work area. This approach uses a couple of laser scanners to trace continuously the position of the human and a control system uses them to define dynamically two working spaces: the robot working space and the human working space. The control system continuously checks for the interaction of the two working spaces and stop the robot whenever the two spaces come in contact. This system is the result of a research carried on by [9].

Therefore the project exploits existing and often well assessed methods to train the robot and to allow the safe human – robot sharing of the same work area. The innovation in the research is its application of many techniques – machine learning, laser scanners, human-robot interaction - to efficiently solve an industrial problem: the automation of GMAW for small batch productions.

The paper is organized as follows: section 2 gives some concise results from a study on the field about a real industrial GMAW; section 3 describes the problem faced by the research; section 4 give a synthesis of the PBD methods adopted with a formal description of the algorithms that will be used for its solution; section 5 presents the setup of the experimental station and the chosen benchmark; section 6 gives the plan for future works.

2 DESCRIBING THE PROCESS STEPS OF THE GMAW

A fundamental step to realize the robot training is to gain as much experience as possible about the process we want to automate. This experience has to be embedded in the library of pre-programmed robot operations from which the movements suited for the specific process will be selected based on operators movements.

A thorough description of the welding process can be found in technical handbooks, because nowadays it can be considered a commonly applied technique. Scarce if no attention is paid in literature to all the other actions that complement the direct execution of the welding.

It was necessary to gain firsthand knowledge about the details of the process. A ‘friend’ factory allowed us to observe several welding operations and even to record them on a movie for future analysis. Therefore all the activities related to the welding were recorded and thank to the direct observations and to some interviews with the workers, it was possible to write out a very detailed Process Flow Diagram (PFD) [10]. Every task represented in the PFD was investigated trying to understand the reason it was executed, the necessity and the possibility of alternative operations.

Avoiding confusing and non necessary details, the set of main processes executed during a GMAW are presented in the following simplified PFD. The symbols used follow the rules set by the American Society of Mechanical Engineers (ASME). The circle stands for ‘operation’, the square shaped stands for ‘inspection’, the arrow for ‘transport and the triangle for ‘storage’.

The process is composed of the following main steps. The first step is to move the part from a storage to the specific frame. Then operators prepare the edges to be joined and establish and maintain them in a proper position by the use of clamps and fixture. In a second time it is necessary to adjust part edges and grind surfaces to facilitate the welding.

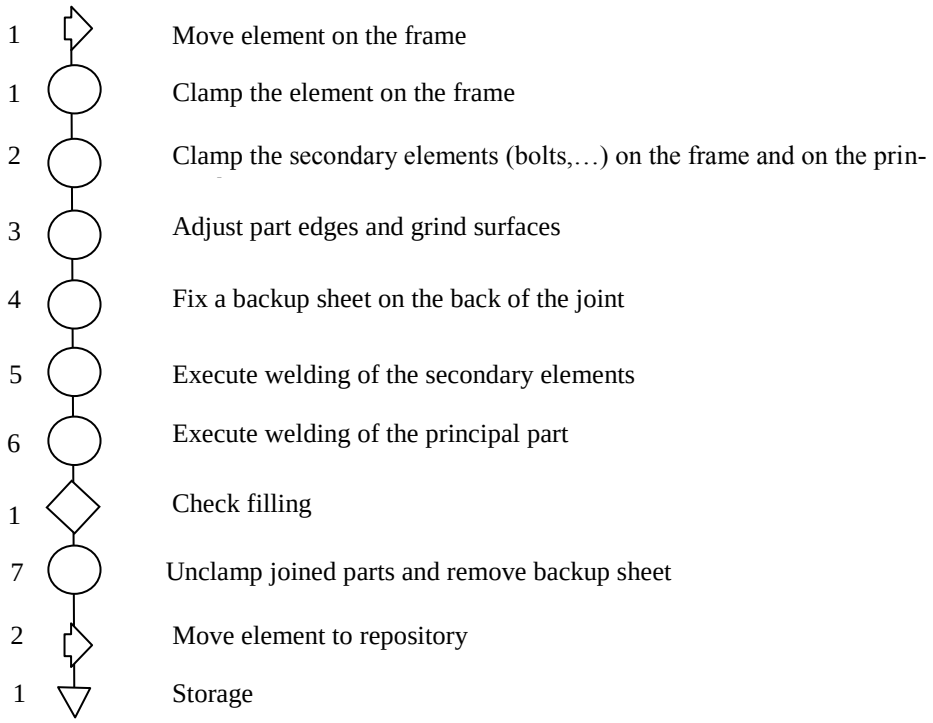

FIGURE 1. Process flow diagram of a complete manual welding process

The third step is to fix a backup sheet on the back of the joint to prevent the spillage of weld metal. The four step is the actual welding.

GMAW technique is quite simple, since the electrode is fed automatically through the torch; in fact this operation requires only that the operator guide the torch imparting the correct position and orientation along the curve to be welded. It is important to keep a consistent contact tip-to-work distance (the stick out distance), because a long stick out distance can cause the electrode to overheat and will also waste shielding gas. Stick out distance varies for different GMAW weld processes and applications. The position of the end of the contact tip to the gas nozzle are related to the stick out distance and also varies with transfer type and application. Another very important feature of the welding process is the orientation of the gun : it should be held so as to bisect the angle between the workpieces. The travel angle, or lead angle, is the angle of the torch with respect to the direction of travel, and it should generally remain approximately vertical. However, the desirable angle varies depending on the type of shielding gas used [11].

After the welding process the operator must unclamp joined parts and remove backup sheet, than the joined part is moved and clamped to another frame for check test of filling, if it is good and without imperfections the part is move to a storage location.

FIGURE 2. The still from a video made by the authors. The welder is going to start the welding of a complex joint in a hard to reach area on the workpiece

It is important to thoroughly extract the features of GMAW technique, as the preliminary and subsequent operations of the process are executed by the human operator, while he/she hand over the welding to the robot.

During the observation of the process it is apparent that human operator measures the distance to hold the welding gun and the speed with which to move on the basis of their sensory perceptions, mainly but not exclusively the sight; this is impossible for present industrial robots that must therefore make reference to a pre-existing data set (e.g. to set the parameters of distance and speed).

Another critical element is the inclination of the gun as well as the different ways of gripping the gun dictated by the convenience of the operator carrying out the operation (with one hand, with two hands), the robot does not have similar problems and can maintain the same inclination of the gun observed from the operator's demonstration.

3 THE PROBLEM DESCRIPTION

The problem that present research confronts is the enabling of a human-robot semi-automated process described by the following points:

1. The human operator fix the workpiece on a standard frame without any accuracy (the position of the workpiece relative to a reference coordinate system changes with every new part).
2. The human operator gives some orders to the robot about where to weld, how many welding tasks, the kind of material to weld (change the stick out distance and the gun orientation).
3. The human operator executes some test welding showing the exact pose of the torch and the trajectory to follow.
4. The human operator moves to a safe position, out of the welding zone, but not necessarily out of the reach of the robot (out of the maximum workspace attainable by the robot).
5. The robot moves the torch to the points indicated by the human being and executes the welding.
6. The robot return to a safe position and the operator makes a visual check of the welding quality and, if it is the case, ask for some rework.

The execution of all of these process steps should not be in this exact order. It is supposed that task 3 be executed and replicated a small number of times by the welder on some test parts. Also some general commands and parameters, independent by the individual execution of the process, like the kind of material welded, are given during the initial phase.

After this prototypal execution of the welding, in the following implementations of the full process the robot has learnt the welding trajectories and need only to know the exact initial points and the final points as they depend on the position and orientation of the workpiece with respect to the fixed reference frame used to orient the robot.

The problem can therefore be subdivided in a number of sub-problems that can be separately solved:

- Guarantee the *safety* to the human operator inside the robot workspace by avoiding that the robot would enter inside a given safe area surrounding the operator (exclusion space). The exclusion space position should be updated dynamically following the operator movements.
- Implement a *machine learning* system based on multi-cameras observation of the welding gun trajectory, handed by the human welder and detected by using markers mounted on the torch.
- Implement a *user interaction* system by which the human operator be able to give orders and indicate key points on the workpiece.

- Put together the solutions of each sub-problem in a comprehensive control system that supervises all the robot actions by working on a higher level with respect to the embedded robot controller.

The safety issues can be solved making reference to existing, thus seldom applied in factory, commercial solutions of virtual fences made by a couple of scan lasers. This solution will be empowered by a dynamic safe space generator as described in [12]. The robot learning and the user interaction sub-problems are addressed by using PbD methods and are discussed in the next section. The 'put together' problem is not addressed in present paper because it can be seen as a problem of industrial application of the research results and is left to the robot industries willing to implement the proposed methods. Its solution is not trivial and surely time consuming. The nice aspect of being a scientist is the chance to avoid the less enjoyable problems.

4 TEACHING THE ROBOT TO WELD

Quoting [7]: "Current approaches to represent a skill can be broadly divided between two trends: a low-level representation of the skill, taking the form of a non-linear mapping between sensory and motor information, which we will later refer to as "trajectories encoding", and, a high-level representation of the skill that decomposes the skill in a sequence of action-perception units, which we will refer to as "symbolic encoding"."

The welding task requires both approaches to be thoroughly executed. The transfer of the torch to the initial welding point, its positioning with the correct pose and the disengaging at the end of the welding require "symbolic encoding" because they are complex tasks with obstacle avoidance problems but are executed differently from the robot with respect to the human and correspond to the execution of commands. The trajectory of the end effector in this phase is not interesting for the process execution. The commands make reference to logical attributes of spatial relationship, like: 'perpendicular to', 'at a given distance', etc.

The welding activity by itself is a simple task corresponding to only one action that cannot be decomposed further. Nevertheless it requires the robot to exactly follow the operator's torch pose along a complex trajectory and it is therefore a problem of trajectory encoding.

At this point, the robot can start working together with the human co-worker in the welding station. The welding station would (should) be only partially automated by leaving to the human the task of handling the parts to be joined and to the robot the task of welding them.

There is a large literature about PbD and even numerous examples of applications covering different kind of robot use, from automated guided vehicle to the reproduction of human activities like playing tennis, football or even face movements [13][14][15]. Despite this amount of research effort, if one visits a modern factory he/she will witness that the way industrial robots are programmed is always the same as twenty years ago. A programmer make the robot perform the tasks by tele-operating it. The robot movements are recorded in a program. Since then the robot will repeat the same movements with a technique called *playback* that, for sake of precision, is just the same a PbD method.

In the Handbook of Robotics it is complained that a large effort has been done investigating 'how to imitate' and 'what to imitate' in applying PbD [16][17][18][19][20], while 'who to imitate' and

‘when to imitate’ remain unexplored. In other words a inadequate attention has been paid to the type and amount of experience the teacher should have. The same for the time chosen for the demonstration.

Trying to apply PbD to an actual GMAW process the importance of solving these last two issues becomes apparent. It is supposed that a small factory could not afford to have a worker exclusively devoted to the robot programming. On the contrary there is surely one or more well trained welding operators. In present research it was decided that the robot teacher has to be the welder. It was also decided that during training the welder would have to behave exactly as she/he is accustomed to in a standard welding. This approach is surely ambitious. The reason that leaded to this approach is that the set of possible movements during the welding are greatly restricted.

Nevertheless there are still some issues to be solved. After the observation and the analysis of manual operations, as described in section 3, the following significant points can be stated:

- The welder have to be always in a position where the working area be utterly visible without interruption of the line of sight.
- During the repetition of the same task, the welder can use different ways to grasp the welding gun, single or two-handed, depending on his/her posture during the work. As an example in fig. XX the welder uses his second hand for holding on to the fixed frame because he is leaning out too much.
- The welder changes frequently the starting position from which to execute the task using the legs. In this way he/she overcome the fact that human arm has a workspace and a configuration space by far smaller than the robot arm.
- The welding speed, the posture of the gun and the distance between the tip of the gun and the joint change significantly from one replication to another.
- The welder does not behaves like an actor. In a movie, it is common to see unrealistic dialogues in which both actors speak in front of the camera instead of looking each other in the eyes.When working on the weld the operator does not pay attention whenever the cameras line of sight are blocked by his/her body.

Also the execution time for the demonstrations poses a number of problems. There are two possibilities:

1. the welder executes several welding manually and the replications are used to infer the automatic tasks and weld trajectory by building a spline that interpolates the acquired trajectory points and tool orientations, using the minimum squares method;
2. the welder works from the start together with the robot and, just before the welding, points out the spots to be welded with a marker, the robot then select and executes the proper pre-programmed welding task.

The case one has an important drawback. If the production is limited to a few products (let’s say below the hundredth), if one has to buy and install both the robot and the manual welding machine, used only for the demonstrations, if the operator has to wear tute, mask, and gloves just for the demonstration, then there is scarce convenience in executing some welds by hand and some

by robot. On the other hand, the case two can be seen as a machine learning application and requires a grater deal of interaction human – robot, therefore the worker should be aware of the way the robot works. Furthermore there are no replications and there is the risk that the process repeatability could not exceed the human repeatability. In present experiment, the chosen solution is a mixture of both: interaction to impart symbolic commands, previous replications to learn the welding trajectory.

5 EXPERIMENT SETUP

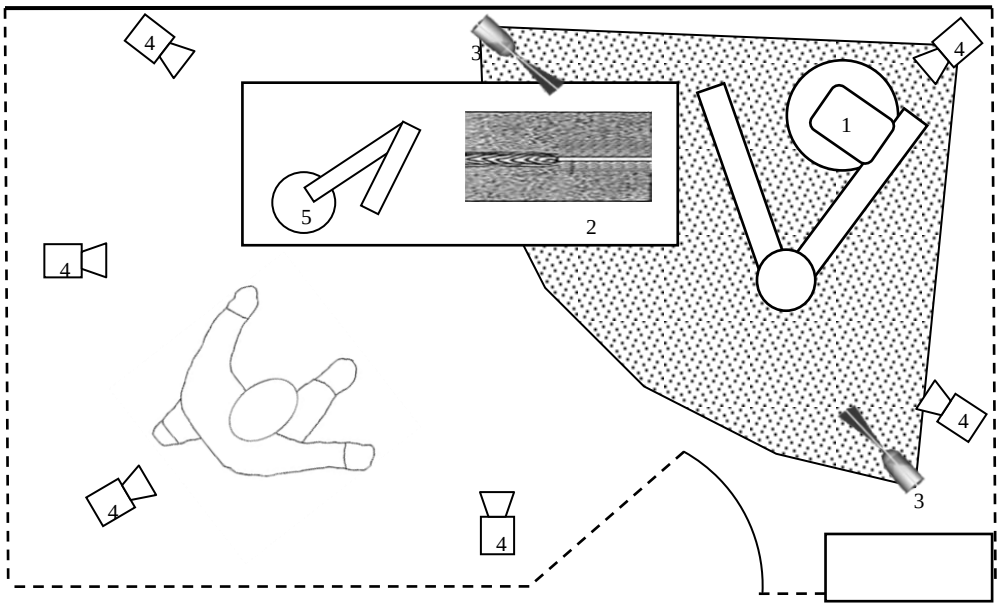

FIGURE 3. Layout of the laboratory experiment reproducing a welding area with a robot interacting with the human operator. 1) NS16 Robot; 2) workpiece; 3 laser scanners; 4) camera, 5) CMM.

The experiment is developed in the research project AMICO, funded by the Regional Government of Piedmont (Italy). The work area will be set up in the laboratory of Production Systems at the Polytechnic of Turin.

The experiment consists of several elements arranged in an area properly fenced and alarmed, as required by the safety laws. The area is arranged to allow the simulation of the welding process by human-machine cooperation: leaving enough space for the work of both. There is also a calibration system made by a CMM.

Fig. 3 shows the elements that will compose the workstation. There is a Comau robot (1) to simulate the welding process, equipped with a welding gun. The NS16 Comau robot is dedicated to

applications where highest accuracy and rapidity are required, as assembly, handling, and arc welding processes.

There are the workpieces (2) to be welded. For the interaction between human and industrial robot the position and orientation of both must be known to avoid any collisions. For the detection of the human position, two laser scanners (3) should be used. In [12] a procedure is proposed for the detection of human being: with a range laser scanner the rough position of humans can be captured. This can be verified using a matrix of safety shutdown mats. With marker-based object-tracking and vision-based tracking algorithms the head and the hands of a human can be localized very precisely. In this way the velocity of the robot can be increased with the distance from the human. If the laser scanner registers one or more persons close to the collaborative safety area (between human and robot reserved areas) or inside the area, the robot slows down or activates the emergency stop.

In the work station there is also a contactless sensor for the identification of welding trajectories indicated by the operator using tools with specific markers to measure position of robot . This contactless sensor uses a multi-camera system, made up of 6 cameras (the minimum number of cameras required in applications of motion capture) (4).

The contactless sensor system concept consists in measuring directly both position and orientation of the mobile object by means of a suitable multi-camera system fixed around the workspace.

Sophisticated self-calibration procedures make this contactless sensor fully autonomous, able to operate in different working conditions with high-dependability. The self-calibration allows to use low-cost cameras, without the need of expensive calibration procedures. The multi-camera system uses fixed focus cameras and passive markers, susceptible to infrared light, distributed on the welding gun, and a software to process the image-data. The vision system, equipped with daylight filters, captures only the marker features of the screenshots relevant for the pose reconstruction. Cameras are placed in such a way that each camera field of view includes all the scene in which the target body is moving. The body reference frame and the user reference frame are each one equipped with their own sets of passive markers, spherical shaped.

The marker centre coordinates (shortly denoted in the following as marker coordinates) are assumed as known and are considered as input data of the contactless sensor data-processing.

The methodological approach is based on the elementary principle, which states that the object pose with respect to the camera optic reference frame can be derived from a single object image whenever the camera has been calibrated and a set of at least three markers not aligned is detected. Both the camera calibration model and the object pose - with respect to the camera optic reference frame - can be derived from a single object image whenever a set of markers is detected, distributed in the three-dimensional space and in a number suitable for the number of degrees of freedom of the camera calibration model to be estimated.

An algorithm has been derived by [21], which allows to measure the moving body reference frame pose with respect to user reference frame and to continuously update both the calibration model and the pose of each camera, tracking their slow time variations. Both the camera number and the marker number have been assumed largely redundant in relation to the minimum value strictly necessary, in such a way to get an instrument at the same time robust and accurate.

The workstation is equipped of a Coordinate Measuring Machine (CMM) (5) to validate and confirm the pose measured by the contactless sensor.

Defined work area, it is necessary define the main benchmarks that authors intend to make with this equipment. For sake of generality, the pieces are not derived from industrial samples, but they are geared to reproduce standard welding joints. In this way it can be shown that the system is capable of performing any type of welding. Fig. 4 presents examples of the most common classes of welding joints.

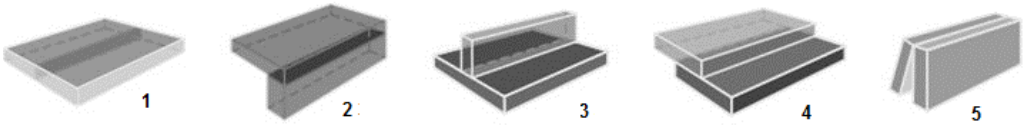

FIGURE 4. Traditional welding joints as represented by [2]: butt joint (1), corner joint (2), tee joint (3), lap joint (4) and edge joint (5).

6 FUTURE WORKS

The paper presents only the state of the study so far and the objectives of the research. The workstation has to be completed and the different parts should be made working in agreement each with the others.

There are still some issues to be solved regarding the transfer of different data by wireless technology and the choice of the filter that should filter only the frequencies of the light emitted by welding. The main and more relevant work to do refers to the definition of a set of symbolic commands to be given to the robot during human interaction. These commands should be reduced to a minimum, as the teacher should be, by choice not an expert of robot programming.

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