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# Intuitive Welding Robot Programming via Motion Capture and Augmented Reality

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**Abstract**: In this paper the authors present a method to equip small and medium enterprises with a highly flexible product line to automate their production through a robotic welding application. The goal is to program a welding robot offline, similar to manual welding. To create the welding application, the workpiece is placed on a programming table and the welder traces the sheet metal joints with a position tracked pointing device. For simulation of the process, virtual weld seams are simultaneously displayed in the video stream of the Augmented Reality camera. The trajectories of the virtual welds are recorded, converted into executable robot code, loaded onto the robot therefore making an immediate machining of the workpiece possible. With this method, robot programs can be created very quickly, easily and cost-effectively, which makes robot production economical even for mass-individualization.



*Keywords:* Industrial robots; Augmented reality; Welding; Programming by demonstration; Motion capture; Off-line robot programming

## 1. INTRODUCTION

In recent years, small and medium enterprises (SMEs) in the welding sector are confronted with a changing market. The products are becoming more complex and a higher degree of individualization will be requested by the costumer. This leads through smaller batch sizes up to single part production and requires a highly flexible production. (Liu and Zhang, 2015)

In most cases a manual based arc welding production is the only way to compete. Manual arc welding can be a monotonous job and lead to permanent damage to health. For instance, Ray (2016) came to the conclusion, that in the welding process of special steel types, hexavalent chromium (Cr6) is emitted and will be absorbed by the organism of the worker. It turns out that Cr6 is harmful to health in the long term. Halasova *et al.* (2012) assumes, that the level of chromium in the blood of workers is increasing significantly if they are regularly in contact with Cr6 during welding tasks. In their study, the subject's Cr6 concentration was between 0.032 and 0.182 µmol/l, which was significantly higher than in the control group. It has been shown that individuals exposed to Cr6 on a professional scale suffer DNA damage from it and the regenerative capacity of the DNA is reduced (Sudha *et al.*, 2011). Staff absenteeism due to illness or accident can lead to delay of orders or production faults, which result in high costs for the employer. In order to protect the health of the employees and the ability to compete, the production process must be changed. One possible solution is a semi-automated production line consisting of human and (lightweight) robots. The robots should be able to be used flexible and quick for various welding tasks in order to avoid production bottlenecks and to support workers. The question that arises here is why the method described above is rarely used today, even though robots are becoming cheaper and manufacturers offer new lightweight robots with high functionality. These robots are promoted by their manufacturers as particularly versatile, quick deployable and easy to program. The robot systems have been improved significantly in terms of usability and manufactures have integrated additional functions like programming by demonstration (PbD). However, programming is still a task that requires highly trained personnel. Appropriate training courses or new employment of specialized staff are very expensive and often cannot be afforded by small companies. In addition, PbD is still very time-consuming and the required process steps are uncommon and unusual for small welding companies. These factors can discourage many companies from implementing the new technology.

In recent years, new technologies such as virtual reality (VR), augmented reality (AR) and mixed reality (MR) have been established in the gaming industry. Virtual reality technology lately has been used in connection with industrial robots to simulate robot movements or production processes and thus improve user-oriented perception. (Michas, Matsas and Vosniakos, 2017)

A common software for developing VR or AR applications is Unity 3D. This software is used, for example, in a project by Pan *et al.* (2016) to simulate an entire robotic welding cell, including the production flow in an industrial research project. Another example of the fusion of welding applications and AR can be seen in Antonelli, Astanin and Teti R. (2015) The publication describes how a worker was guided to the exact position where he should carry out a spot welding via an AR interface.

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Ni *et al.* (2017) went even further and showed in their publication an AR robot programming application which has been enhanced by a haptic module in the shape of a robot end-effector. This provides force feedback if the virtual robot touches a virtual surface in the simulation. The above examples show that VR and AR technology enables complex processes to be simulated realistically and provide the user with real-time information. This enables workers to handle complex tasks more intuitively and with less training time.

## 2. APPROACH

Our idea for solving the aforementioned problems is to let the arc welder program the robot himself, by means of an AR robot programming method, which is very similar to well-established hand welding.

An experienced arc welder can rely on the skills he has developed during his career and knows best how to weld a part to obtain a dimensionally stable, high quality weldment. The interaction of a professional welder with a robot promises considerable potential for efficient small batch production of welding products, combining the advantage of human experience with the precision and repeatability of the robot. Additionally, by using a welding simulation, the process can be performed in a safe environment, to prevent accidents and protect the worker from inhaling toxic fumes that endanger health, as described in Section 1. These aspects enable an increased productivity with existing staff, to accustom the workers to new production methods and to keep the level of employment constant.

## 3. THE DETAILS

In this section the method is described in detail. First, the overall process is explained and how the robot program is created. Afterwards, the steps required to run the program on the robot are shown.

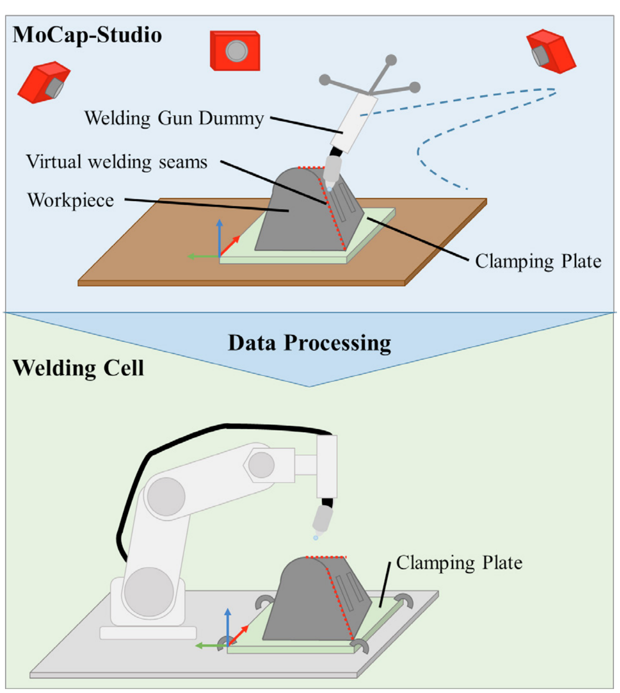



Fig. 1. Illustration of the whole process for AR robot welding applications.

### *3.1 Overall Process*

There are two main steps that are carried out in two spatially and temporally separated processes, that correspond to offline programming. An illustration of the overall process can be seen in Fig. 1. The first step takes place in an office environment, called Motion Capture (MoCap)-Studio. Trajectories for the welds on the workpiece blank are recorded with the pointing device, whose spatial position is traced. The pointing device has the same size and shape as the welding gun that will be used later on the robot. After recording, the trajectories are converted into an executable robot program. The second step takes place on the shopfloor and the program is executed by the robot on the blank. The generated program can be used to edit all blanks from the batch.

### *3.2 MoCap Studio*

The MoCap-Studio is a room containing a table and a clamping plate to fix individual sheets for the blank. The position of the clamping plate is referenced with a coordinate cross, consisting of several infrared (IR) markers. The whole room is being observed by four IR cameras, which are the main components of the MoCap system. The system is prepared with a special calibration tool by tracking the tool within the space near the table. By means of this process, the system calculates the dimensions of the room and references all cameras to a global origin. Afterwards, the clamping plate is fastened to the table and the mounted, physical coordinate system is added in the software via the corresponding IR markers. The coordinate system has several measuring tips, which serve as calibration points for the pointing device. The exact position of the tips were already determined with a portable measuring arm using a FARO laser line scanner and the tool centre point (TCP) is precisely calibrated by repeatedly probing with the tip of the pointing device.

The coordinate cross on the mounting plate can be interpreted as a basic coordinate system for the later robot application. Since the coordinate cross of the clamping plate is relative to the original coordinate system of the MoCap system, the plate can be rotated to any position to generate the greatest possible comfort for the user without affecting the results (see Fig. 2). The individual surfaces, which are already provided with welding spots, are fixed to the clamping plate and the virtual welding process can begin.

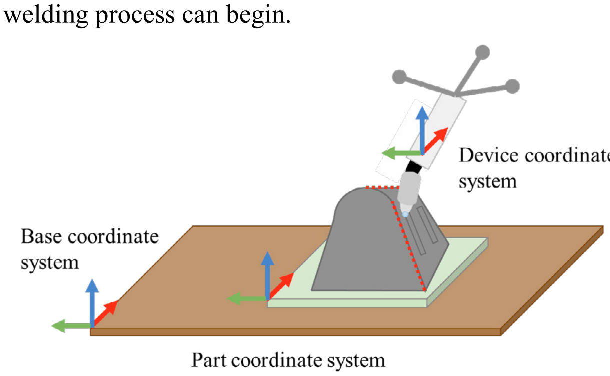



Fig. 2. Illustration of the different reference coordinate systems.

This virtual process differs only slightly from the procedure and the required motor skills from the conventional use of manual welding equipment for gas metal arc welding. Virtual weld seams will be recorded by guiding the tip of the pointing device over the sheet metal joints. The AR-toolkit of the application generates virtual artefacts at the weld seam waypoints and places them over the image captured by an video camera (see Fig. 3). The trajectories of the welding tracks are displayed in real time and help the user to evaluate whether the tracks have been set correctly. After all virtual welding paths have been created, the user can inspect the trajectories in detail and optimize the trajectory if necessary.

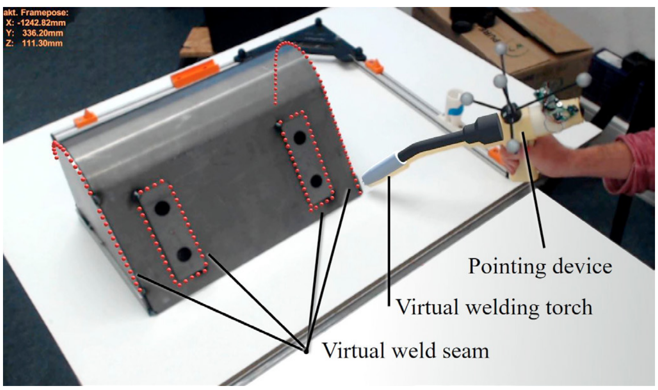



Fig. 3. Workpiece with virtual weld seam (line of red spheres).

### 3.3 Converting Process

The virtual welds are represented by several individual waypoints, with each point having six degrees of freedom (6DoF). The points are used to describe the current pose of the welding torch. By merging the individual waypoints, a complete robot path planning can take place. The following steps are required to generate a robot program:

First, the base coordinate system of the robot must be determined in a way that the robot can reach every pose. If no position can be found, the workpiece must be re-positioned in the real scenario or placed on a turntable. After defining the robot base coordinate system, a special software is used to smooth all trajectories by using fly-by points and removing outliers. All necessary welding parameters such as movement speed, power or wire feed speed, etc. are then defined for the respective trajectory. Subsequently, the individual robot commands for the corresponding sub-sections must be defined. As an example, it could be determined how the robot should behave between the end of a trajectory and the beginning of a new trajectory (linear, circular over an additional waypoint). The angles of the robot are calculated with an inverse kinematics solver for every single waypoint, prohibiting singularities. If all parameters are defined, a program will be generated and transferred to the controller of the robot.

### 3.4 Implementation

The clamping plate is now placed in the welding cell in front of the robot. The coordinate system of the clamping plate needs to have the correct distance and orientation (see section 3.2) to the robot base coordinate system. To validate if the coordinate systens line up, a calibration run is performed with the robot. Herefore, the robot probes the three calibration peaks on the coordinate cross of the clamping plate. The coordinates of the three points are recorded and checked for correctness using a software tool. The software tool outputs the calculated error and shows whether and how the plate must be repositioned. If the calculated error is within the tolerance range, the generated robot welding program can be executed and the blank or the entire batch can be welded. For a better understanding of the overall process is shown in Fig. 4.

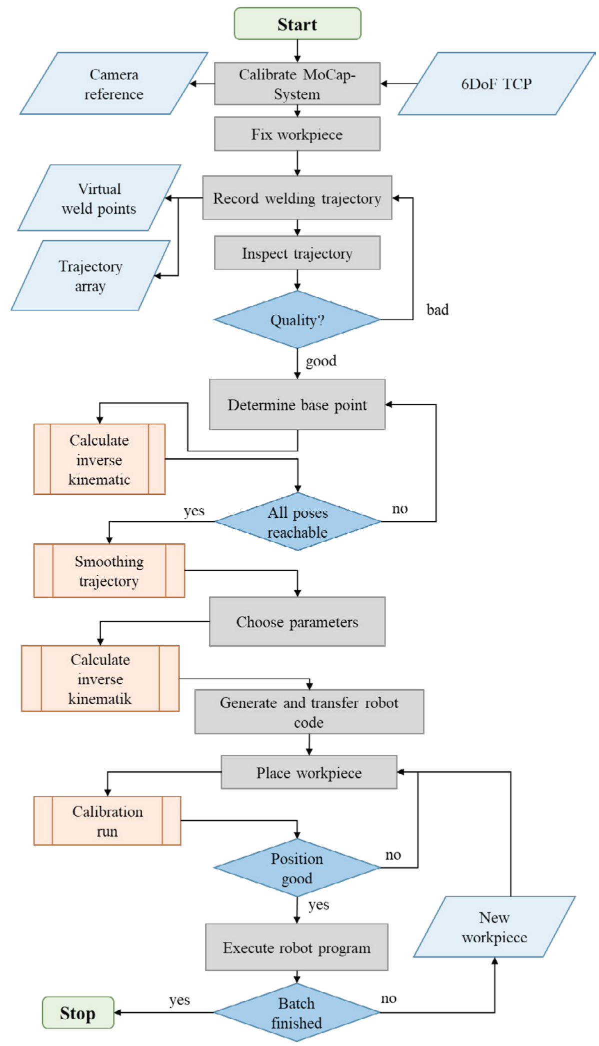



Fig. 4. Process flow diagram for the presented AR robot welding method.

## 4. RESULTS

The quality of the recorded trajectories is decisive for the successful implementation of the entire concept. The quality is influenced by the framerate of the recording and human influences while recording. The repetition-rate must be high enough to be able to reproduce the weld seam. Furthermore, small human-induced shaking movements should not directly impact the robot path planning, as this makes the application less efficient and can also damage the mechanics in the long term. Based on the previous considerations, the following questions were raised, which are to be clarified by an experimental investigation.

1. Can the method described in Section 3 achieve a sufficiently high resolution of the trajectories, and does the trajectory contain outliers that can adversely affect robot path planning?
2. How does the data acquisition rate change the resolution of the trajectory and what are the limits of the system?

The experiment consists of reproducing a given spline function as good as possible with the trajectories recorded by the MoCap system. For this purpose, a wooden template was used in which four defined spline functions were engraved with a laser cutter (see Fig. 5). Due to the deepening in the wood, the splines could be reproducibly traced with a pen-like tracking tool. The accuracy of the system has already been investigated in Müller *et al.* (2018) and is between 0.3 and 0.5mm.

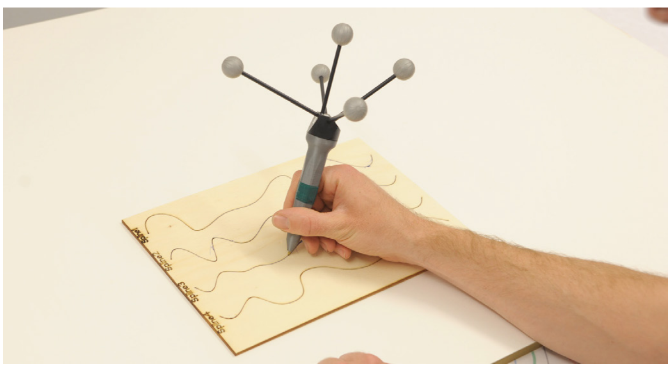
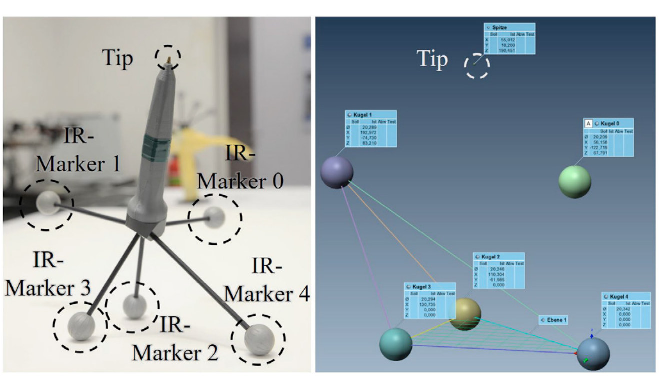


Fig. 5. Wood panel with engraved spline functions

This tracking tool is equipped with five passive infrared markers, which are captured by the MoCap system's four cameras to capture the position of the tracking tool. In order to place the pivot point exactly into the tip of the tracking tool, all reference points were already measured with a portable measuring arm using a FARO laser line scanner (see Fig. 6). The measured reference points could then be compared with the coordinates of the infrared markers from the MoCap system and the pivot point could be repositioned in the tracking software.




(a) Tracking tool (b) Measuring points

Fig. 6. Measurement of the tracking tool.

The four given splines are now struck over with the tracking tool using four different data acquisition rates (see Section 4.1.1). This results in 16 measurement series and each series was repeated three times to obtain an mean.

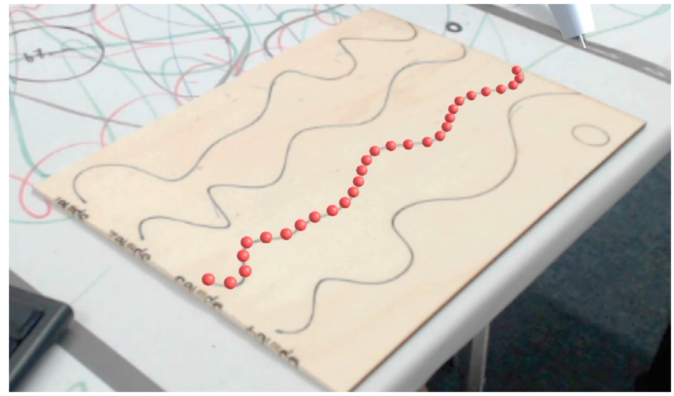


Fig. 7. Virtual weld seam on template (10mm).

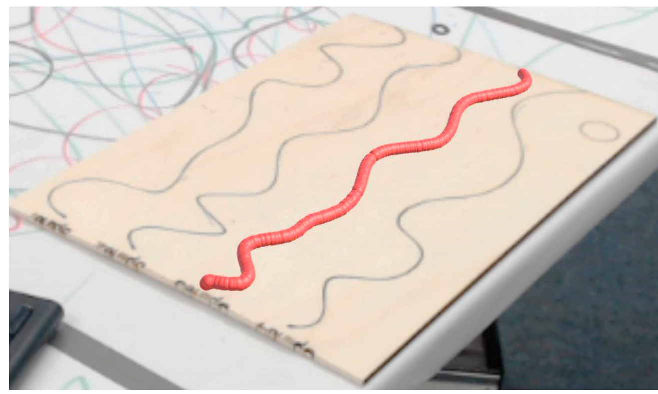


Fig. 8. Virtual weld seam on template (1mm).

Fig. 7 and Fig. 8 show two screenshots from the AR application of visualized trajectories with different data acquisition rates. The red artefacts represent the virtual weld and the distance between the artefacts corresponds to the selected data acquisition rate. The operator can easily and intuitively check whether he has recorded all necessary trajectories and whether they follow the sheet metal joints correctly.

#### *4.1.1.Data Acquisition Rate*

In this context, this refers to a method to control the resolution of the trajectory. When a point is recorded, it receives a spherical area around itself with corresponding radius (e.g. 1mm, 2mm 5mm, 10mm). Only when the pivot point of the tracking tool leaves this area or reaches the sphere surface, a new point with its own sphere will be created.

#### *4.1.2. Determination of Measurement Error*

In order to determine the absolute measurement error of the system, it is necessary to adjust the data of the recorded trajectories. The X values of the spline function were matched with the recorded trajectories. For this purpose, the values of the trajectories were interpolated. This procedure causes the point density to decrease when the graph has a steep gradient. Due to the method described in Section 4.1.1, the raw data set has a homogeneous point distribution with respect to the covered way.

Fig. 9 (upper part) shows an example of the ordinate deviation (blue) of the recorded trajectory of spline function 1. The Spline function is shown in black, and the red dots show the points recorded with the MoCap system using a data point acquisition rate of 1mm.

It is noticeable that the error increases with rising X position and from a X value of 188mm there is a parallel displacement of the graph of about 3mm (abscissa). In addition, outliers listed by way of example in Table 1 could be identified.

If the distance between the trajectory and the spline function is determined over the shortest distance, the deviation, with the exception of the outliers, is within a range of 2.12mm to 3.08mm.

Table 1. Relevant outliers (Sp1, 1mm, rec. 1)

| Outliers | X Position (mm) | Error (mm) |
|---|---|---|
| 1 | 55.5 | 1.1 |
| 2 | 78.5 | 1.0 |
| 3 | 164 | 1.5 |
| 4 | 188 | 2.2 |
| 8 | 234 | 0.9 |

*4.1.3. Factor Influencing the Data Acquisition Rate*

Fig. 9 (lower part) shows spline function 1 and four trajectories recorded with the MoCap system. The trajectories were recorded with different data acquisition rates and all data points are unprocessed.

It can be seen that the radial distance between the individual points is relatively constant at the data acquisition rate of 2 mm, 5 mm and 10 mm. Only at a data acquisition rate of 1 mm, the radial point distance is variating significantly. It's remarkable that, as already mentioned in Section 4.1.2, the error magnitude in the X direction increases with rising X values. However, no factorial correlation can be determined, since the deviations fluctuate both positively and negatively. The data acquisition rate has no apparent influence on the magnitude of the error in the X direction. It can only be determined, that the spline function within the first 30 mm can be mapped very well through the MoCap trajectories. In addition, the number of outliers increases with the increase of the data acquisition rate.

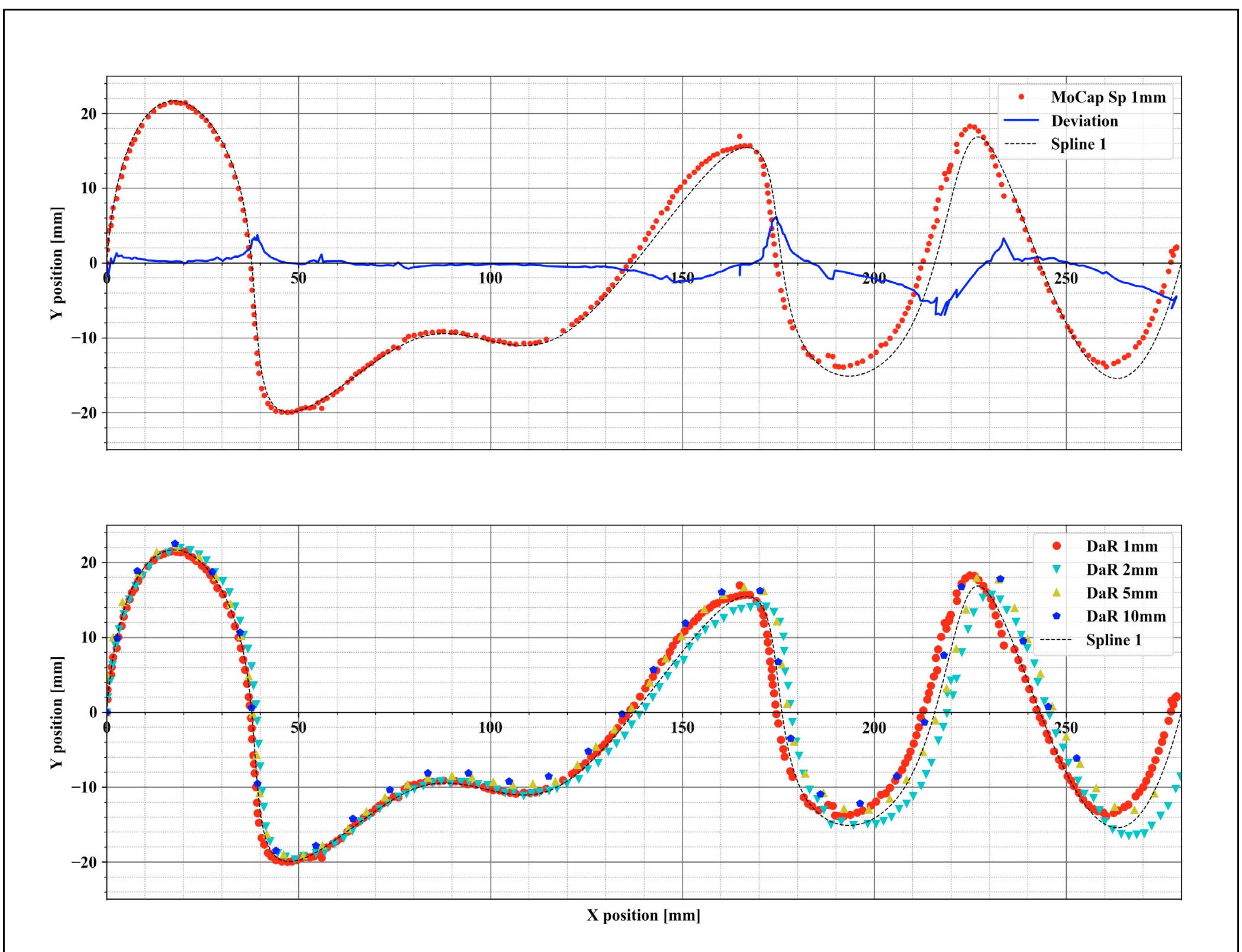



Fig. 9. Deviation from the spline function 1

## 5. Conclusion and Outlook

In this paper an AR technology based methodology that enables creating a robot welding program in an intuitive way was introduced. The process is strongly inspired by manual arc welding and aims to perform the process by a professional welder. It was also shown which process steps are required to transfer the created virtual welds into an executable program. In addition, it was shown how to set up the welding cell. In order to check the quality of the virtual welds, a study was conducted in Section 4.

The study showed that the overall quality of the method described here is sufficient to establish a basis for robot path planning. However, the trajectories must first be searched for outliers by use of filter algorithms. The outliers must be removed by interpolation in order to ensure a smooth trajectory. Furthermore, the cause of the factorial X-value deviation must be identified and controlled by hardware optimization or software compensation.

The trajectory with the data acquisition rate of 2mm shows the best compromise between resolution and homogeneous point distribution. This data acquisition rate is recommended for further investigations in which components are to be welded that range in size from 200mm to 1000mm. In addition, it could be interesting for further investigations to know which transmission factor can be used to consciously control the quality of the trajectories in order to obtain the ideal trajectory for the welding task of the robot. For higher-precision welding tasks, where the accuracy of the MoCap system is no longer sufficient, an active path correction could be installed at the robot end-effector. In addition, the set-up process in the robot cell could be accelerated by a tool positioning aid. an example of such a positioning aid can be found in (Charrett, Kissinger and Tatam, 2019). By means of an optical sensor, the position in the plane and the range resolved in all three translation axis are used to determine the relative position between the robotic end-effector and the workpiece.

Further research activities focus on conducting a comprehensive study with a welding robot and the presented programming method. The quality of the weld shall be checked on the real part and a direct comparison shall be made between manually and mechanically welded parts.

## ACKNOWLEGEMENTS

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