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Original
Enhancing the Quality of Manual Spot Welding through Augmented Reality Assisted Guidance / Antonelli, D., Astanin, S.. - 33:(2015), pp. 557-562. (9th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '14) [10.1016/j.procir.2015.06.076].

Availability:
This version is available at: 11583/2629480 since: 2016-10-24T11:32:16Z

Publisher:
Elsevier

Published
DOI:10.1016/j.procir.2015.06.076

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12 October 2026

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Procedia CIRP 33 (2015) 556 – 561

www.elsevier.com/locate/procedia

9th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '14

Enhancing the Quality of Manual Spot Welding through Augmented Reality Assisted Guidance

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Abstract

Manual spot welding loses the comparison with automated spot welding, not because of a higher execution time, but due to an inferior quality of welded points, mostly a low repeatability. It is not a human fault. Human welder is compelled to operate without having at disposal the knowledge of significant process features that are known by the robot: exact position of the welding spot, electric parameters to be adopted for every specific point, quality of the welded spot and, based on it, possible need for repetition of a defective weld.
The research shows that, using an augmented reality device, it is possible to display this very data to the human operator, in order to enhance the manual process execution. The adopted device is a tablet mounted on the welding gun. It displays the working area seen by the built-in camera. The image is augmented by the superposition of computer generated images of the welding spots and their properties. The state of the spot (welded or not) and its execution quality (good or defective weld) is transmitted by some graphic features, like point color, size and way of blinking. The paper describes the algorithms used in the development of the program for this application, focusing on the problem of real time localization of the welding gun position. The augmented reality application was actually installed on a experimental station by a welding gun manufacturer and the results of the tests are presented and discussed.

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Selection and peer-review under responsibility of the International Scientific Committee of “9th CIRP ICME Conference”

Keywords: Augmented reality ; Welding ; Quality Monitoring

1. Introduction

New working paradigms are nowadays established in the industrial manufacturing enterprises under different names, Total Quality, Lean Manufacturing, World Class Manufacturing. Among the most significant concepts, there is the idea that quality must shift from the inspection on the final product to the process assurance during production. Appropriate operative strategies are put in place, aimed at improving the production process quality by making it repeatable and error-free. Specifically, the tools have to be mistake proofing (poka-yoke) and the variability of the process should tend to zero.

In the assembly process, the strategies to reduce process variability are easier to implement and more effective on the automatic production lines, compared to semi-automatic or fully manual lines. The greater flexibility of manual assembly is offset by the human operator's contribution in introducing mistakes and stochastic variability.

Resistance spot welding is widely used in the automotive world to join the metal sheets of the car body since it is versatile, reliable and above all economic. The process is used both in manual and in automatic stations.

The quality assurance of the process is obtained by a careful design of electric parameters of every individual spot and by welding quality control systems, adopted by nearly all tool manufacturers. The subject has been thoroughly studied by researchers and industrial companies [1]-[4]. Unfortunately these methods are effective only for automatic Spot Welding, as they rely on the possibility of interacting in real time with the welder and on the exact knowledge of where is the next point to be welded.

A solution to improve the manual welding should pass through the empowerment of the human operator. We should pass him/her the same information that is used in the robotic

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doi:10.1016/j.procir.2015.06.076

cell. Procedures must be adopted in order to minimize the possibility of human error.

Our research aims at demonstrate that Augmented Reality (AR) makes it possible to fulfill these targets by:

- directing the operator to the exact point where the welding has to be performed;
- preventing selection errors of the welding program by controlling the welding parameters with the same control unit used by the robot (possible only if the position of the welded spot is known);
- allowing, to customize the parameters of every single point to optimize the spot quality;
- ensuring, through the use of the Welding Quality System (WQS), the respect of joint requirements in terms of mechanical resistance and metallurgical properties;
- notifying the operator and the supervision system of bad spots;
- preventing welding until the clamp is not on the correct position and alignment.

There are further targets that are not relevant from the scientific viewpoint but they are crucial for the acceptation of the system by the industrial users: low cost of the solution and easy to use by untrained operators. We make use of a commercial tablet and of a small set of markers located in the operational area. We developed a devoted user interface that can assist the operator during and after the welding process. The application is non invasive and no additional task is required to the human welder with respect to the traditional way of working.

The paper will describe briefly the state of the art, both in Spot Welding control as in the use of Augmented Reality applications to support assembly processes. Then the problems and the solutions adopted are presented and eventually the implementation in an actual industrial welding cell is shown.

2. State of the art and known issues of manual welding

2.1. Spot welding in automatic and manual assembly stations

The spot welding process consists of forcing the passage of high current (typically between 6 kA and 15 kA) between two sheets pressed by two electrodes made of a copper alloy CuCrZr (Fig. 1).

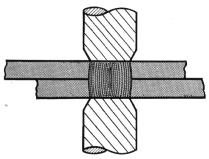

Fig. 1. Scheme of the joint formation during spot welding.

The shape of the electrodes determines position and size of the joint. Since the area that presents the greatest resistance to the passage of current is located at the contact interface between the sheets, it develops the greatest amount of heat by Joule effect with the consequent melting of the core and the formation of the welding spot.

The welding system makes use of a current transformer fed at mains frequency (typically 380-500V 50/60Hz for welding phase) whose secondary, thanks to the reduced number of coils is capable to deliver the high currents necessary for welding. In the case of medium-frequency welding, the power of the transformer is instead obtained by using a Medium Frequency Inverter that transforms a three-phase mains voltage (380V - 690V 50/60Hz) into a voltage at 1000Hz - 1800Hz frequency, with significant advantages both from the point of view of energy efficiency and of current control.

Spot welding in the automotive plants is used for car body assembly and is carried out on dedicated assembly lines. The production of large series is executed by industrial robots, which allow the achievement of an excellent level of repeatability and ensure the correct selection of the welding parameters, as each point is associated with a specific welding program.

Automated spot welding is supported by a Welding Quality System (WQS) that measures and monitors in real time intensity of the output current and other variables, indirectly inducing the size of the core, the presence of weld defects, the electrode wear, the dynamic strength, the energy and other parameters that contribute to the quality of the weld [5], [6]. The welding parameters considered in the indirect control are current, pressure against the electrodes, welding time and voltage. The quality is assessed by comparison with a library of different welding samples and it is usually performed by using neural networks or fuzzy logic inference (every toolmaker has its own solution). The main types of welds that can be classified are: spray, good, glued and short circuit.

In small batch production areas, spot welding is performed manually by skilled operators using manual clamps. The problems that afflict manual welding are:

- limited precision in the positioning of the welding points compared to predetermined positions;
- limited speed in the execution of operations;
- limited ability to control the execution of all the points provided;
- limited number of welding programs usable (up to a maximum of 2);
- limited possibilities to check on the correct selection of the welding program;
- consequent impossibility of using the WQS.

2.2. Augmented reality assisting assembly processes

All the issues presented here are related to the lack of information exchanges during the process. Operating times are so fast (seconds) that it is impossible for the operator to consult an informative display in the meantime. It is necessary

to put the information just in correspondence with the position of the spot to be welded.

AR is a technology that enhances the real world with virtual elements (computer-generated). It has three basic properties [7]: combination of real and virtual objects in the real environment; realignment of real and virtual objects; interaction working in real time.

[8] provides a survey on recent application of AR to industrial assembly. AR proved effective [9] as a guide to assist the execution of assembly operations if compared with the consultation of traditional instruction manuals on paper or even on monitor. The main research issues to be addressed, are the recognition and tracking of assembly components and the interaction among the operator, the components, and the system. For the recognition of the assembly components and for tracking, most reported AR guidance systems make use of fiducial markers, which have to be put either on the assembly components or on the jigs and fixtures [10], [11].

The marker adoption is not the only approach in order to identify the parts to be assembled, because they could be recognized directly. Nevertheless it is the method that guarantee the maximum assurance of a correct match among the observed objects and the assembly parts.

Researches were conducted on the interaction between the operator and the system. [12-14], namely on the choice of a natural and reliable interaction mechanism.

[13] is particularly significant for present study because they do not limit to present an AR application but try to build a procedure for an assembly training system that is AR-based. They describe and analyze the assembly job, subdividing it in tasks and sub-tasks, and the generation of assembly instructions. [14] propose a pose estimation method for the correct rendering of the assembly operations.

With few exceptions the research on AR is more oriented on the technology employed to insert visually credible artificial objects in a real environment. This is an answer to the question: 'how'? With the advancement in the AR supporting technology, both hardware and software, it has become possible to have recourse to commercial solutions in order to build AR applications. There are still two open questions: 'what' to display and 'why'? The questions should be answered in the inverse sequence. Decide the kind of assistance required by the worker during the assembly, select the information to display, chose the most appropriate AR device.

3. The proposed solution

In order to state what kind and level of assistance is required by welding operator, an extensive set of observations and interviews were performed at GF-Welding, a tool maker.

The workflow of the activities performed during the welding process is the following. The operator holds the electrodes in a reference point outside the operation theatre, then move the tool to the first point with a right pose. The electrodes are opened in the wider position to facilitate insertion on the sheet. They are closed to the working configuration (minimum opening). When the tool is positioned correctly and centered exactly on the welding spot, the operator selects the welding program (intensity of current, welding time and pressure over the electrodes). Then the welding starts. The tool reopens and, if there is room on the sheet, the operator repeats a new point. Eventually, the operator move back the tool to the initial reference position.

The workflow is described in Fig.2, using 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, the triangle for ‘storage’ and the half circle for ‘waiting time’.

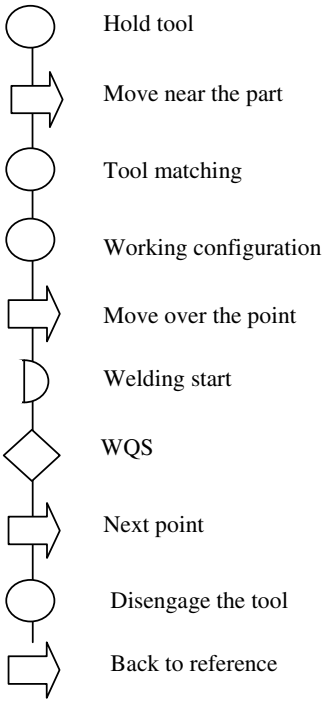

Fig. 2. Workflow of the spot welding manual process

The end user expects the following outcomes from the solution: simplify the operator's work, increase productivity, improve the repeatability of the welding points, improve welding quality. The mere introduction of AR in the process addresses some of the objectives. The quality can be improved only by activation of WQS also in the manual welding. The system can work only if the exact position of the welded spot is known, because every point has different execution parameters. The position can be found as a side effect of the use of AR. In order to superimpose virtual objects to the real world, it is necessary to locate with fairly good accuracy the position of both the tool and of the display. This datum could be passed to WQS that therefore receives indirectly the knowledge of position where the next point is going to be joined.

Once stated the scope of the application, it is time to define exactly the set of messages that will be displayed to assist the welding operator. Due to the peculiar nature of the AR, the format we use to display the message is as much important as the datum itself

A typical defect of most AR systems is the overflow of information. In other words the interface provides the operator too much facts and figures in an annoying way. The welding operator has a few seconds before moving to the next point, therefore the messages should be few, of immediate understanding, possibly graphical and non textual. After some interviews with company technicians, the list of messages in Table 1 was selected, after carefully discarding everything deemed unnecessary.

Table 1. List of the messages provided to the welder.

Stage of operation	Information	Metric
Overview to prepare assembly	Position of all the spots	CAD rendering
Welding gun positioning	Position of the target point	CAD render highlighted
	Suggested movement	Symbol (arrow)
	Gun position and orientation	Dynamic symbol
Welding execution	Selected program	Symbol (blink)
Spot quality analysis	Spot quality	Symbol (color)

3.1. Selecting the technology for AR

There are various methods to overlay virtual elements on the vision of the real world. There are at least three types of displays for AR: head-worn displays, both transparent and opaque, handheld displays, projectors. Virtually all the transparent displays (optical see-through) suffer from low contrast, and are not able to fully occlude the elements of the real world. This fact limits their usefulness in cases when the ambient light is not fully under the user control. See through goggles suffer parallax errors, because cameras' optical axes do not coincide with the those of the eyes. The use of these devices requires a period of adaptation for the eye, known to be tiring. The use of projectors requires controlled light conditions and no obstacles between projectors and the work surface. It is not always acceptable in cramped environments.

Having in mind these constraints, we chose to use a portable display because it is a cost-effective solution, do not impose physiological fatigue on the operator, can be integrated with the welding clamp, the application is not bound to the specific geometry of the workpiece (Fig. 3).

The tablet was mounted on the welding gun by using a rigid support that should not allow relative displacements among the tablet and the gun. As a result, the position of the tablet's on board camera is rigidly associated to the position of the welding gun and eventually of the electrodes.

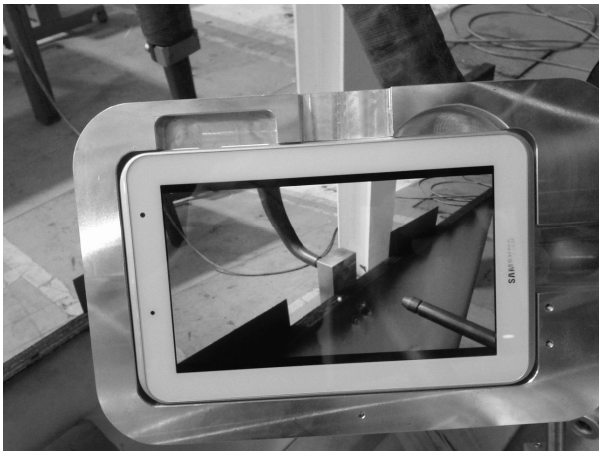

Fig. 3. The tablet mounted on the welding gun, with its built in rear camera used for displaying the real view of the clamps (maximum opening position).

3.2. Definition of the dataflow for the AR assisted solution

The rationale behind the proposed solution is described by the scheme of Fig. 4. The welding gun position is obtained by means of optical tracking of markers placed in the corners of the working area. It is also the possible to integrate the observation with data from encoders mounted on the welding gun. Not all the degrees of freedom can be measured through encoder and therefore, presently we have not tested this solution. An external camera observes the welding zone and the AR engine augments the image by adding the welding instructions. The embedded camera of the tablet can be used instead of the dedicated external camera. We used this option to avoid placing an additional camera in the working area.

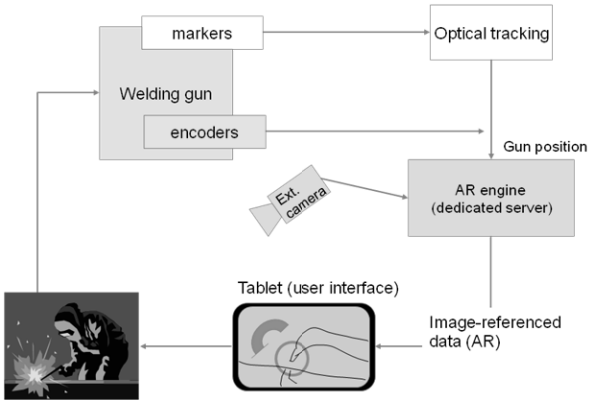

Fig. 4. Schematic representation of the information flow.

4. Camera calibration

To provide a credible combination of real and virtual objects it is crucial to perform a camera calibration both of the internal camera geometric and optical characteristics (intrinsic parameters) and of the position and orientation of the camera frame (extrinsic parameters) with respect to a reference system [8].

The intrinsic parameters take into account the camera distortion, too. They can be considered with good approximation as constants. Extrinsic parameters are variable as the camera is mounted on the welding tool that is movable. There is therefore the necessity for an initial calibration to be performed at the beginning of the work and of a real time calibration to update in real time the camera position. The two procedure are performed using different methods.

Initial calibration makes use of OpenCV standard routines [15], while iterative refinement of the control points [16] is under testing. We used as initial calibration tool either a black and white chessboard or a symmetrical circle pattern. In Fig.5, the last version of the calibration object is presented, with superposed in the four corners the fiducial square markers that are used to determine position and orientation of the camera.

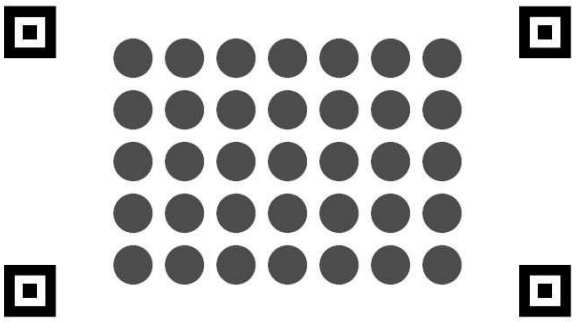

Fig. 5. The calibration circle grid that constitute the canonical image with easy to localize control points and the square fiducial markers.

The calibration object (circle grid or chessboard) is observed by many different angles. On the object it is possible to individuate a set of points $\boldsymbol{P}_i$. The transformation between the object coordinates (X_i, Y_i, Z_i) and the image coordinates (u_i, v_i) is obtained through a projection matrix [P] in the homogeneous coordinate system.

$$[P]=[K][R][t] \tag{1}$$

Where [R] and [t] are the rotation and translation matrices and are extrinsic parameters, [K] is the calibration matrix and is composed by intrinsic camera parameters.

$$[K]=\begin{bmatrix} f_x & s & p_x \\ 0 & f_y & p_y \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

The image coordinates (u_i, v_i) must be corrected for the lens distortion that is assumed to be radial and tangential. Neglecting nonlinear effects, the distortion parameters are presented as a distortion matrix [D].

$$[D]=\begin{bmatrix} k_1 & k_2 & p_1 & p_2 & k_3 \end{bmatrix} \tag{3}$$

The meaning of the distortion parameters can be found in [15]. The matrices are identified all together by comparing several (around 10) different snapshots of the same object. This is the first step in the camera calibration and is used to assign the intrinsic parameters of the camera. In Fig.6 the chessboard used for calibration is shown. To check the effectiveness of calibration, some virtual cubes are displayed on the figure.

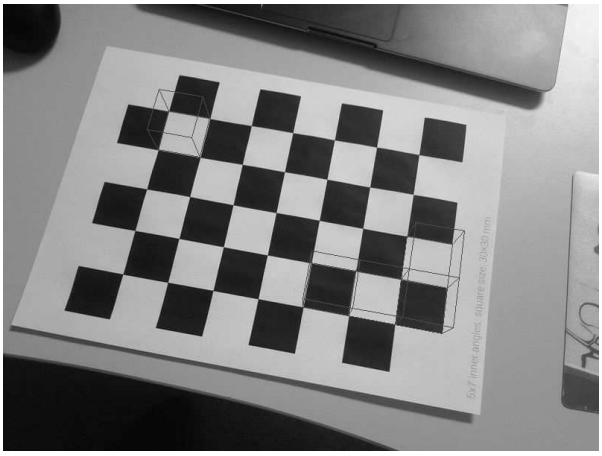

Fig. 6. The camera calibration. To check the quality of the calibration some virtual 3D blocks are displayed on the calibration chessboard.

The second step is to determine again the extrinsic parameters of the camera, position and orientation, exactly for every frame. As the camera has a frame rate of 30 images per second it is important to adopt fast algorithms in order to keep up with the visualization rate. In this second step the parameters to be identificated are the coefficients of the matrices [R] and [t] and can be obtained by using only four fiducial markers in the corners of the image.

5. Results and conclusions

In the following figures, Fig. 7 and 8, the system working is shown in demo mode. The central cross, representing the tip of the electrode is moved on the circles that compose an “A” letter. The markers are four crosses in the corners The grid of point is barely visible by human eyes, are not detected by the AR application and are used only for accuracy testing. As can be seen the four markers have been recognized and highlighted in both images. Virtual circles are superimposed on the image. The position accuracy can be easily determined in Fig.8, where the underlying grid has been made thicker.

When the tip of the electrode is near a point to be welded, a tracking circle start to widen. When the electrode is on the exact spot the circle has its maximum width and change color.

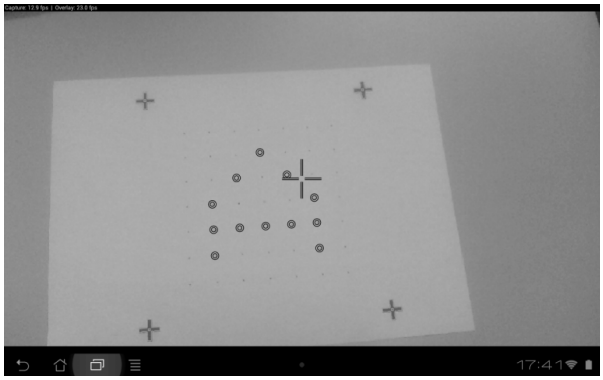

Fig. 7. The basic application in demo mode on an Android tablet display. A rectangular grid of points is printed on the paper. Point sizes and colors change dynamically as the tool point move over them. Frame-rate is 24.8 fps.

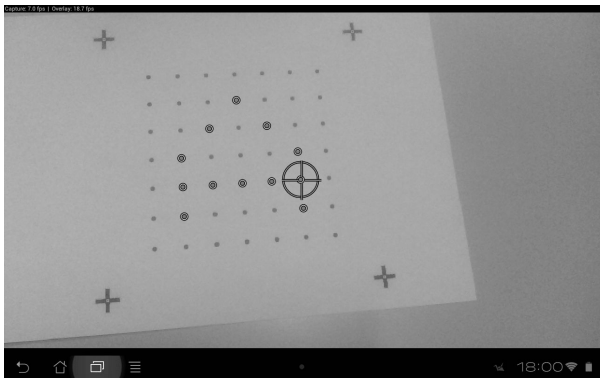

Fig. 8. The basic application in demo mode on an Android tablet display. The tool tip is on the right point and the tracking circle has its maximum width. Printed grid of points have been made thicker for sake of visualization.

The application was tested in the factory GF-Welding, a welding toolmaker, with some benchmark pieces, after having mounted the tablet with the AR program on the welding gun. A professional welder tried to execute the welding points and, after a short training time, was able to repeat the operation without errors.

There are two further developments that are yet to be provided in order to implement this application in end user industries.

The markers must be redundant in order to work on parts that are larger than the camera display. It is necessary to guarantee that there be always 4 markers in the view area.

The real sheets to be welded are not planar, therefore the point positions in the space must be read by a CAD file provided by the process engineer. For simplicity of implementation the markers should be at a equal distance and on the same plane. A frame with these characteristics should be added to the welding zone, studying how to make it less invasive.

Once completed the engineering of the application it will be possible to develop extensive test plans on real production parts to assess its actual potential.

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