Abstract

In the last years, efforts have been focused towards new approaches for the automation of gas metal arc welding process parameters. In this framework, an innovative welding system based on a 3-axis motion device and a vision system consisting of a video camera, a laser head and a band-pass filter has been developed and implemented to recognize the desired features of weld joints, such as geometry and dimensions, and automatically adapt the welding process parameters according to these features. This paper focuses on a real case study of the railway manufacturing industry related to the welding process of a bogie frame. Through the employment of 3D Motion Simulation, the identification of a suitable reconfiguration of the system through the substitution of the 3-axis motion device by means of an industrial robot is studied in a totally digital framework. Simulation of the welding process allows calculation of robot kinematics, collision detection and motion planning.

1. Introduction

Gas Metal Arc Welding (GMAW) processes require accurate selection and setting of the suitable welding parameters. Most often, this task is still accomplished by human operators who need technical experience and skills to optimally select the required welding parameters for the given boundary conditions.

In the last years, efforts have been focused towards new approaches for monitoring and automatic adjustment of the GMAW process parameters, based on the use of different sensors and processing algorithms [1-5].

In this framework, an innovative welding system based on a 3-axis motion device and a vision system has been developed and implemented (Fig. 1). The vision system, consisting of a video camera, a laser head and a band-pass filter, allows to capture pictures of the weld joints. Image processing algorithms have been developed to recognize the desired features of the weld joint, such as geometry and dimensions. This information is used for automatic decision making concerning the selection of the most suitable welding parameters for the specific welding task.

In this research work, the developed GMAW system is implemented with reference to an industrial case of the railway manufacturing industry, consisting in welding of a bogie side frame. The two parts to be joint are characterized by large size and complex geometry, as they need to be joint along a curved path.

The vision system is employed to capture images of the working area and automatically recognize the relevant joint gap features. The automatic decision making software procedure allows to determine the path to be followed by the welding torch and to set the proper welding process parameters according to the output provided by the vision system.

With reference to the real industrial case study, the software procedure developed at the laboratory facilities is experimentally tested on the available GMAW equipment.
3D Motion Simulation is firstly employed for the digital analysis of the current system behaviour and setup of experimental tests on the laboratory equipment.

To allow the implementation of the innovative GMAW system within the railway manufacturing industry, a physical reconfiguration of the system is required to overcome the strong limitations in terms of part size and joint complexity related to the existing 3-axis motion device.

A 3D Motion Simulation based approach is applied to support decision making on the most suitable reconfiguration of the system for the specific application in a totally digital framework. Through the employment of 3D Motion Simulation, the identification and verification of a reconfigured welding system based on an industrial robot is studied in a totally digital framework.

2. The Automated Gas Metal Arc Welding System

The automated GMAW system developed at the laboratory of the University of Naples is provided with a modern vision system and innovative software capabilities aimed at the automatic adjustment of welding parameters according to the characteristics of the specific welding application.

2.1. The vision system

The innovative gas metal arc welding system is equipped with a vision system consisting of a video camera, a laser head and a band-pass filter (Fig. 2).

By projecting a laser stripe on the desired object and capturing an image while the stripe is moving it is possible to calculate the object geometry based on the shape of the laser stripe. This can be usefully applied to recognise the desired features of weld joints, such as geometry and dimensions, to be used for automatic decision making on the setting of suitable welding parameters for the specific welding task: this is particularly helpful in case of multipass welding, complex seam tracking, etc.

The video camera employed for the vision system (Guppy F-033C by Allied Vision Technologies) is provided with a CCD sensor with 658x494 pixel resolution, and a IEEE1394a interface for communication with PC, with transfer rates from 100, 200, 400 Mbit/s, frame rates over 60fps. A proper optical lens able to reduce image distortion has been mounted.

The laser stripe is emitted by a red laser diode of class 3 with 15 mW power and wavelength around 640nm. The wavelength has been selected taking into account the need to reduce the emissions within the spectrum generated by the welding torch. To obtain a stripe instead of a point, a cylindrical optical lens was applied.

The band-pass filter has the role of excluding all the frequencies which are outside a 10nm range centred on the laser source frequency (from 637,441 nm to 648,359 nm), so as to reduce noise.

The conceptual scheme of the visual system based on laser and video camera is shown in Fig. 3.

2.2. The image processing

In order to automate the gas metal arc welding process, a proper software tool has been developed. The algorithm is based on mathematical functions by which the input data, i.e. the images captured by the vision system, are processed in order to give as output the desired features. Based on these features, process parameters such as welding torch position, torch speed, or electrical parameters can be determined based on a suitable decision making procedure, such as a neuro-fuzzy approach [6-8].

Image processing is performed using image and data analysis tools to reconstruct the joint profile starting from the acquired image. Each tool is employed for a specified task, such as:
Fig. 4. The acquired image after digital filtering.

Fig. 5. Graph of the joint gap section (xy coordinates).

- Edge detection: it recognizes the joint contours based on pixel intensity local change;
- Threshold: as the image is still blurry, a filter cuts out the grey scales under a defined threshold to get a clear image;
- Lookup table: the aim of this filter is to convert the image into a black and white (binary) picture.

The image obtained after digital filtering appears as shown in Fig. 4. On this image, further processing has to be performed to extract the desired features, in particular:

1. Image normalization: to correct the inclination of the camera through a rotation matrix;
2. Image stabilization: through a low pass filter set to 1.5 Hz;
3. Detection of the desired features: the desired features are detected on the x-y graph of the joint gap section (Fig. 5) and depend on the type of application (e.g. edges of the joint gap, center of the joint gap, minimum height of the weld joint, etc.).

Based on the detected features, useful parameters of the welding process are determined. As an example, in case of simple seam tracking, welding position is set in correspondence to the center of the joint gap, while in case of multipass welding, the welding position is set in correspondence to the minimum height of the weld joint, because this is the point where the next pass should be performed. Automatic adjustment of the selected parameters is then performed by implementing a closed loop control.

2.3. The laboratory welding equipment

The GMAW equipment available at the laboratory facilities of the University of Naples, including the welding torch and the vision system, is mounted on a 3-axis motion device and a fixed worktable. This configuration involves limitations concerning:

- the maximum dimensions of parts: the working space related to the run of the 3 motion axes is 3000 mm x 400 mm x 400 mm;
- the geometrical complexity of the parts and the desired welding joint: only 3 axes are available and, consequently, the possible orientations of the welding torch are much constrained.

3. Railway Manufacturing Industrial Case Study

The aim of this research work is to study the innovative GMAW system implementation to a real industrial case study of railway manufacturing. Decision making on the best system configuration for laboratory experiments and the required reconfiguration for the real industrial application is supported by a 3D motion simulation approach, according to the following steps:

- Case study identification and data collection
- 3D motion simulation: experimental setup configuration
- Physical tests on laboratory equipment
- 3D motion simulation: GMAW reconfiguration

4. Welding of a bogie side frame

The railway manufacturing industrial case study consists in the realization of an automated welding process to join the platband and the core of a bogie side frame. This welding process is traditionally carried out manually, which requires high expertise by the operator and long times to be performed. Automating this process would give considerable advantages in terms of productivity and repeatability, but it presents difficulties related to the following aspects:

- The complex welding path (see yellow curves in Fig. 6) as the two parts to be welded have a curved profile;
- The variability of the joint gap width along the welding path.

The two profiles are not exactly coincident because the core curved contour is obtained by cutting a metal sheet according to the desired profile, while the platband shape is produced by bending a metal sheet. The resulting distance among the two curved profiles is not the same along the welding path, and the size of the joint gap width cannot be exactly predicted in advance. According to the joint gap width at each point along the welding path, process parameters such as torch position, wire feed rate and electrical parameters should be adjusted to make the axis of the welding torch coincide with the axis of the joint gap and to deliver the right amount of fused metal. This adaptation allows to obtain weld beads with good mechanical properties in a rapid automated manner.

Fig. 6. Bogie: the welding path is highlighted in yellow.
5. Existing GMAW System 3D Digital Simulation

Experimental testing for the implementation of the innovative GMAW system to the selected case study is required. To study the best setup for the tests to be carried out on the train bogie components, 3D digital simulation has been employed using the 3D model of the GMAW system shown in Fig. 8. The model is a 3D device provided with joints able to reproduce the motion required to perform the welding process. This allows to configure the best setup for the physical experimentation of the GMAW process taking into account the characteristics and limitations of the system available at the laboratory facilities.

The first limitation associated to the available GMAW system concerns the size of the parts to be welded. The bogie frame components have quite large dimensions compared to the GMAW system, therefore only a portion of the should be considered to perform welding experiments. 3D models of the components were realized and the proper portions to be cut for the tests were selected as shown in Fig. 9. 3D motion simulation was then employed to find the best part and torch positioning allowing to weld the desired parts.

An important constraint to take into account is that the vision system should always precede the torch so that it can recognize the trajectory and the gap width, so that the software adapts the welding parameters according to the vision system output. Collision detection was employed during simulation of the welding process to find the path allowing the torch to reach all the required points without hitting on the other surfaces of the part.

After the simulation of several scenarios with different part positioning and torch orientations, the final setup for the experimental tests for automated GMAW implementation was identified (the setup is shown in Fig. 9).

The torch orientation has been modified with a rotation of 45° along the x axis so that it is able to reach all the points along the joint moving on the xy plane. The vision system has been accordingly positioned in front of the welding torch with an inclination of 45° to focus on the joint gap between platband and core.

6. Physical Experimentation for Automatic Adjustment of Welding Parameters

The implementation of the innovative automated GMAW system for welding on the bogie frame required physical experimentation on a test part to develop the automatic adjustment of welding parameters. Tests were performed on the GMAW equipment available at the laboratory facilities according to the configuration resulting from the simulation activity described in section 5.

The developed software described in section 2.2 was implemented to perform automatic adjustment of process parameters - such as welding torch position, torch speed, wire feed rate and electrical parameters - through the acquisition of proper information gathered by the vision system mounted on the GMAW equipment.

The closed loop control to adjust the welding torch position according to the output obtained by the processing algorithm performed on the image captured by the vision system is designed according to the scheme in Fig. 10.

During the welding process, the vision system acquires the trajectory on a xy diagram. Interpolation between consecutive points is realized through a spline adding 10 points between every 2 points. For each x-y position coordinates, the image processing algorithm gives as output also the corresponding value of the gap width. Some examples of these values are shown in Table 1, while Fig. 11 and 12 show the path acquired through the vision system and the values of the gap width along the path.
Fig. 10. Closed loop welding torch control scheme.

Fig. 11. Path acquired through the vision system.

Fig. 12. Values of gap width along the welding path.

Table 1. Some values of gap width acquired through the vision system for every xy coordinates. Measures are in mm.

| X    | Y    | GAP |
|------|------|-----|
| 244,923 | 95,399 | 2.292 |
| 259,499 | 99,99 | 2.292 |
| 259,599 | 91,355 | 2.292 |
| 291,71 | 93,599 | 2.939 |
| 294,499 | 99,994 | 3.951 |

According to the features extracted by the image processing algorithm on the pictures captured by the vision system, automatic adjustment of the welding parameters is performed to improve the quality of the weld joint.

In particular, the measurement of the joint gap width is used on one hand for the alignment of the welding torch position to the middle of the joint gap, and on the other hand for the adjustment of the other process parameters such as wire feed rate, welding torch speed and electrical parameters. When the gap width is higher, the welding torch speed is lowered or, alternatively, the wire feed rate is increased and the electrical parameters are properly adapted (e.g. by setting a higher voltage, etc.).

The results of the experiments were used to implement the software for the automatic parameter adjustment during welding of the bogie side frame.

To make the process industrially applicable to the railway manufacturing industry, however, the laboratory 3-axis configuration is too limited, as it would not allow to weld the entire bogie frame due to the large dimensions (3000 x 3500 mm) and the complexity of finding a proper torch position. Additional motion axes and a larger workspace are required for performance improvement.

7. 3D Digital Reconfiguration of the Automated GMAW System

The digital reconfiguration of the automated GMAW system with reference to the specific application of bogie side frame welding was carried out through 3D motion simulation.

A digital simulation environment can reproduce assembly processes with a high level of detail, which is extremely attractive in the field of railway manufacturing [9-10].

In particular, the employment of 3D Motion simulation proves essential to allow for a virtual verification of the activities that a device such as a robot has to carry out [11-14]. It is usefully employed to simulate robot tasks in order to identify the most suitable layout, the proper distance between the robot and the surrounding equipment and to plan safe paths without collisions. This simulation is based on the adoption of kinematics models and collision detection capability. Tasks are created by placing targets at proper locations all over the working zone and assigning to each target the appropriate actions to replicate the robot activities.

Different system configurations were tested on a fully digital basis and their feasibility and performance was analyzed to setup the proper configuration for the robotic welding system according to the scheme in Fig. 13.

According to the features extracted by the image processing algorithm on the pictures captured by the vision system, automatic adjustment of the welding parameters is performed to improve the quality of the weld joint.

Geometrical and functional features of parts and devices are particularly relevant in this type of simulation. The 3D model of the bogie frame was created in the digital
environment, and used to configure and digitally test the best setup for robotic welding.

The robot chosen for this application is a 6-axis robot, Fanuc ArcMate 120iB, with a maximum reach of 1667 mm, payload of 20 kg, repeatability of ±0.08mm. A 3D model of the robot with related kinematics was retrieved to simulate the welding process.

The robot should be equipped with the welding torch and the vision system. The vision system should move together with the torch as it should always focus on the joint gap. One way to ensure that the vision system can always be correctly positioned in front of the welding torch is by linking the vision system to the torch.

In this way, it can be rotated together with the sixth axis of the robot; this rotation can be used to make sure that in every point of the path the vision system is in front of the welding torch, so that it can acquire images of the joint gap and perform the automatic adjustment of welding parameters.

To take into account the position of the laser and the video camera during the entire welding process, the axes of both devices were highlighted and indicated as straight lines: the focus is given by the intersection of the two axes (Fig. 14).

The simulation of the robot welding activity was performed by identifying targets in the 3D space (defined by points with specific orientations); in correspondence to each target, a specified robot task was associated (e.g. processing/welding, via point, etc.).

The identification of the proper targets on the product was carried out taking into account not only the welding torch position, but also the position of the laser/video camera focus, geometrically represented by the intersection of the two highlighted axes, as shown in Fig. 15.

The entire set of targets defined on the bogie side frame to perform the welding process is shown in Fig. 16.

Once all the targets on the product had been defined, reachability analysis was performed. This type of analysis allows to verify if all the targets can be reached by the selected robot starting from its current position.

If some of the required targets cannot be reached, several solutions may be adopted:
- the robot starting position could be modified;
- the robot model can be replaced (e.g. by a larger robot);
- an auxiliary device, e.g. a rail or a gantry, can be introduced in the setup.

In this case study, due to the large part dimensions, the robot was required to reach targets which are up to 3500 mm far from each other: to ensure that the entire bogie side frame is reachable, the robot was placed on a proper rail, whose minimum length was determined based on the results of the 3D motion simulation experiments. According the available standard modules, the most suitable dimension of the rail was set equal to 3900 mm.

In this way, the part size limits were easily overcome, and the robotic welding system could process the entire bogie side frame. The configuration setup of the entire robotic welding system is shown in Fig. 17.

With this reconfigured setup, tasks were assigned to the robot: the tasks are the activities to be performed at each target point, reproducing the entire welding process. 3D motion simulation of these tasks was carried out to verify that the targets can be reached, and it is possible to identify a path without collisions between the welding robot and the product.

The simulation based on robot kinematics and collision detection modules gave as a result the path to be followed by the robot to complete the tasks. This path could be potentially used for off-line robot programming, although the aim of this simulation was to identify the most suitable system reconfiguration and verify its feasibility before the physical industrial implementation of the automatic GMAW system.
In this paper, an innovative Gas Metal Arc Welding system equipped with a vision system consisting of a video camera, a laser head and a band-pass filter was illustrated and implemented with reference to a real industrial case of the railway manufacturing industry. The developed system is able to perform automatic welding process parameters adjustment through a dedicated software procedure according to the information gathered by the vision system.

With reference to the industrial case study, consisting in welding of a bogie side frame, the software procedure developed at the laboratory facilities was experimentally tested on the available GMAW equipment. To allow the applicability of the innovative welding system to the real industrial case study, a suitable reconfiguration of the system was required due to the strong limitations in terms of part size and joint complexity related to the existing 3-axis motion device.

Through the employment of 3D Motion Simulation, the identification of a suitable reconfiguration of the system by replacing the 3-axis motion device with an industrial robot was studied in a totally digital framework.

Simulation of the welding process allowed calculation of robot kinematics, collision detection and motion planning, useful to identify and digitally verify the best configuration for the robotic automated welding system.

Acknowledgements

The Fraunhofer Joint Laboratory of Excellence on Advanced Production Technology (Fh-J LEAPT) at the Department of Chemical, Materials and Industrial Production

Fig. 17. Reconfigured GMAW system: robotic welding setup.

8. Summary

In this paper, an innovative Gas Metal Arc Welding system was studied in a Department of Chemical, Materials and Industrial Production and a band-pass filter was illustrated and equipped with a vision system consisting of a video camera, a for the robotic automated welding system. Useful to identify and digitally verify the best configuration robot kinematics, collision detection and motion planning, replacing the 3-axis motion device with an industrial robot identification of a suitable reconfiguration of the system by welding of a bogie side frame, the software procedure was required due to the strong limitations in terms of part size and joint complexity related to the existing 3-axis motion device.

Through the employment of 3D Motion Simulation, the analysis of a Robotic Manufacturing Cell, In: Proceedings of the 1st CIRP Global Conference on Interdisciplinary Research in Production Engineering - CIRP ICME'12, Procedia CIRP 12, p. 426-431.

Caggiano, A., Teti, R., 2012. Digital manufacturing cell design for performance increase, In: Proceedings of the 1st CIRP Global Web Conference on Interdisciplinary Research in Production Engineering - CIRP 2012, Procedia CIRP 2:1, p. 64-69.

Caggiano, A., Teti, R., 2011. Digital Factory Simulation Tools for the Analysis of a Robotic Manufacturing Cell, In: Proceedings of the 7th Int. Conf. on Digital Enterprise Technology - DET 2011, Athens, Greece, p. 478-485.

Caggiano, A., Teti, R., 2012. Improving the performance of a real manufacturing cell through advanced digital simulation, In: Proceedings of the 14th International Conference on Modern Information Technology in the Innovation Processes of Industrial Enterprises - MITIP 2012, p. 267-279.