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Robotic Seam Tracking for Friction Stir Welding under Large Contact Forces

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Abstract Friction stir welding (FSW) is a solid-state welding process where metals are joined without melting. Heat is generated by friction between a rotating non-consumable tool and the work-piece material, and by mechanical deformation of the material. The process, invented in 1991, provides several benefits over arc welding and other fusion processes: No filler material has to be added, low energy consumption, low distortion and excellent mechanical properties, similar to those of the parent material. The FSW process has hitherto been performed mostly by stiff machines of gantry-type. In this work, however, the use of a 6 DOF robot arm for FSW was explored. This allows for processing of a wider range of seam shapes. However, the compliance of the robot introduces challenges in terms of positioning of the tool subject to large external forces. In the FSW process, large contact forces are necessary to produce frictional heat, to move the tool along the seam, and to counteract the torque induced by the rotating tool. In this context, it is not enough to rely on the robot's internal sensors for positioning, and therefore, an external laser sensor was attached adjacent to the tool in order to detect and measure the position of the seam. The measurements propagated through a PI-controller, yielding changes of the reference positions for the robot. The approach was verified experimentally at TWI Technology Centre Yorkshire, UK, through FSW of thin section aluminium alloys with an ABB IRB 7600 robot.

Keywords: Friction stir welding, Seam tracking, Robotics

1. Introduction

Friction stir welding (FSW) is becoming an increasingly popular solid-state joining process, known for its superior mechanical properties and its ability to join dissimilar and hard-to-weld materials. Informative reviews of FSW in general are presented in [1, 2], and a review of robotic FSW in particular can be found in [3]. The materials are not melted and therefore the heat input is lower. This fact implies lower energy consumption and less distortion than most other welding processes. In FSW, a rotating, non-consumable tool is plunged into the interface of the two materials to be welded. The combination of frictional heat and mechanical deformation of the material, results in a flow of plasticized material around the tool, which is contained between the tool and the surrounding solid material. This produces a high-quality joint which can reach a tensile strength exceeding that of the parent material. Unlike for most welding processes, there is a mechanical interaction between the material and the welding equipment. For FSW, this implies that the actuator operating the welding equipment, e.g., the robot, is subject to high process forces in the order of 1 kN to 10 kN for FSW of thin section aluminium alloys. If a robot is used, this results in deflections of the robot. When this occurs, the internal sensors and forward kinematics are not accurate enough for positioning of the tool.

A common method to mitigate inaccuracy introduced by deflections is stiffness/compliance modeling [4, 5, 6, 7]. This is based on modeling of joint deflections Δq on the form

$$\Delta q = K(\tau) \tag{1}$$

or of Cartesian deflections

$$\Delta x = K(f) \tag{2}$$

where τ and f are the joint torques and external forces, respectively, Δx denotes defelection in Cartesian space, and K denotes some, possibly non-linear, compliance function. To avoid the dependence on expensive equipment capable of accurately measuring the deflections, the clamping method has been proposed [6, 8, 9]. Further, [5] uses arm-side angle measurements, removing the problem of joint deflections. However, these methods do not capture deflections if they occur in the links, or in the joints orthogonally to the movement, in which case the accuracy of the model obtained is reduced [8].

In contrary, in this present paper we propose to measure the FSW tool position in relation to the seam using an external laser seam tracker, attached close to the tool. The measurements were fed back to a position controller. This approach took the deflections described above into account.

The weld trials described herein were based on the stationary-shoulder FSW technique, which is typically used where low heat input and a smooth surface finish are critical. The stationary-shoulder tool is displayed in Fig. 1.

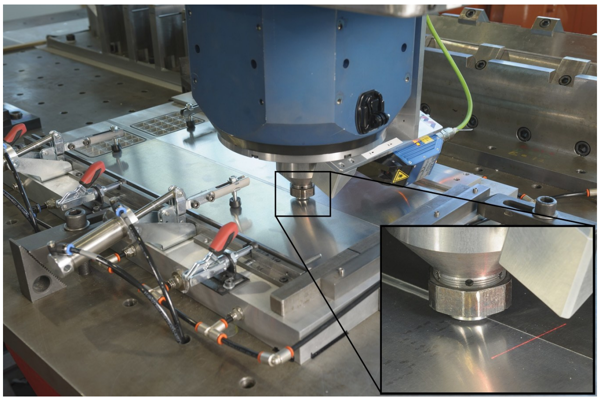

***Fig.** 1. FSW equipment used in the experiments. In particular, the stationary-shoulder FSW tool is magnified in the lower-right figure.*

***Fig.** 2. Overview of the robot cell and the ABB IRB 7600 robot arm with 6 DOF used in the experiments.*

1.1 Problem formulation

In this paper, we address the question whether a robot with deflection compensation could be used for FSW with sufficient accuracy, despite the large machining forces and resulting high deflections. In particular, the FSW tool tip must be within 0.5 mm from the center line of the seam while welding, to guarantee desirable joint properties.

2. Notation

For convenience, Table 1 lists some of the more important quantities used in this work. This notation will be explained in more detail later on, while this list may serve as a quick reference. Further, the coordinate frame used here is shown in Fig. 3.

***Table.** 1. Definition and description of variables.*

Variable	Description
t	- Sample index
h	- Sample period
$\hat{x}$	- Position measured by seam tracker
x_r	- Reference tool position
Δx	- Change of reference position for EGM
x_e	- Position error
x_i	- Time integrated position error
K_p	- Proportional gain of outer controller
K_i	- Integral gain of outer controller

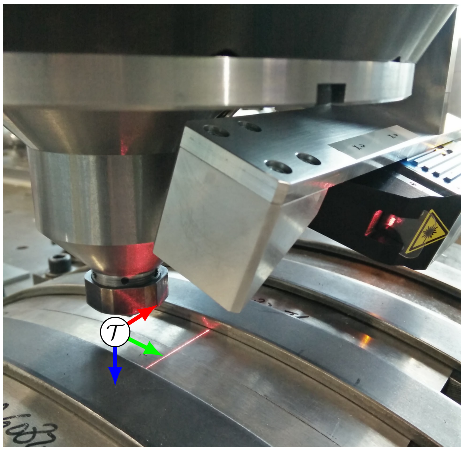

***Fig.** 3. Tool coordinate frame $\mathcal{T}$, $(x, y, z) \leftrightarrow$ (red, green, blue). The z-direction points down perpendicularly to the work-piece material, y is parallel to the seam, and x is perpendicular to the seam and to z. The frame is orthonormal and right oriented.*

3. Method

In this section, the hardware architecture and software implementation, followed by the control design for seam tracking, are described. Previous research on architecture for communication and control in robot cells is presented in, e.g., [10, 11, 12].

3.1 Hardware architecture

An ABB IRB 7600 robot [13], displayed in Fig. 2, equipped with a spindle and an interchangeable FSW tool, was used to perform the welding. The spindle was controlled by a programmable logic controller (PLC). The work-piece material was attached in a fixture in front of the robot, and a force sensor was mounted between the robot's tool flange and the spindle. Further, an external laser seam tracker manufactured by Meta Systems [14] was attached to the robot. It was of great importance to measure the seam position as close to the tool tip as possible, while fulfilling the mechanical constraints that there should be room for the spindle and the seam tracker, and that collision with the fixture should be avoided. In order to achieve this, a mirror was used to redirect the laser beam, both on its path from the sensor to the work piece, and vice versa. This allowed for measurements 3 cm in front of the tool tip. The design is displayed in Fig. 3. A closer view of the seam tracker and the mirror is shown in Fig. 4. In [15], it was shown how to solve the calibration problem between the sensor and the tool flange of the robot.

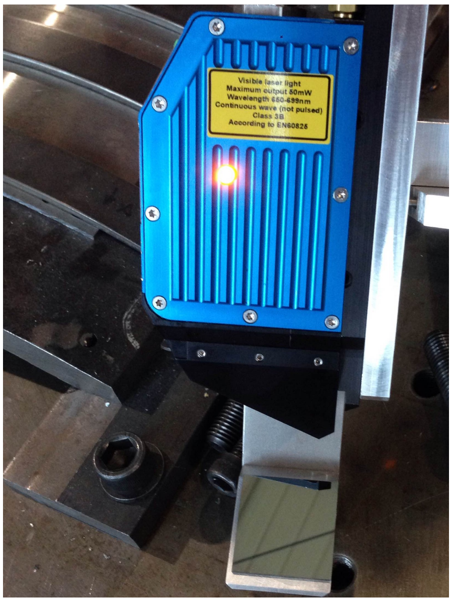

***Fig.** 4. Mirror attached to laser seam tracker used in the experiments. Redirecting the laser beam allowed for measurements closer to the FSW tool tip.*

One dedicated PC was used to run the controller and sensor communication, and a second PC formed a logging server where process data was stored. This arrangement is elaborated upon in Section 6. The ABB IRC5 system [16] was used to run the low-level robot joint controller.

A schematic overview of system prototype hardware is shown in Fig. 5.

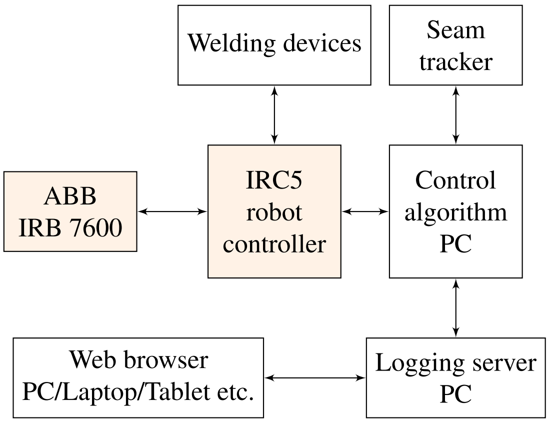

***Fig.** 5. A schematic overview of system hardware. Arrows represent communication channels. Orange components are part of the robotics system. Welding devices include a force sensor, a spindle with a PLC and driver, and a retractable pin.*

3.2 Software implementation

The software implemented can be divided into three main parts; RAPID code and controller configuration of the IRC5 robot controller, control algorithm software, and system logging software.

The robot controller software must be capable of sending and receiving motion data, as well as receiving RAPID program data. To handle motion data the ABB Externally Guided Motion (EGM) interface was used. This interface communicated over an Ethernet/UDP socket and sent data encoded in the Google Protobuf format [17]. A description of protocol buffer encoding in general is given in [18].

When handling RAPID data the Robot Reference Interface (RRI) was used. The RRI communicated over an Ethernet/UDP connection and sent data in a human readable XML format. This interface required a description of the server to connect to, and communication with the controller.

To handle merging of data arriving at different samples and from different sources, a piece of software called labcommswitch was implemented. The purpose of this software was to allow for generic appending of new data sources and sinks in a type-secure way. The protocol LabComm [19] was used for inter-process communication, since it provided a type-secure way of sending and receiving data between processes.

Logging was separated from the algorithm and sensor software. Even though it was possible to run the logging software on the same PC as labcommswitch, this was not done in the current setup, as motivated in Section 6. The server received data from labcommswitch over a websocket connection, as data samples merged to one stream by labcommswitch. Both experiments and associated data could be deleted by using the web interface. Data from running experiments could be plotted in real-time. The web interface could also display data from completed experiments.

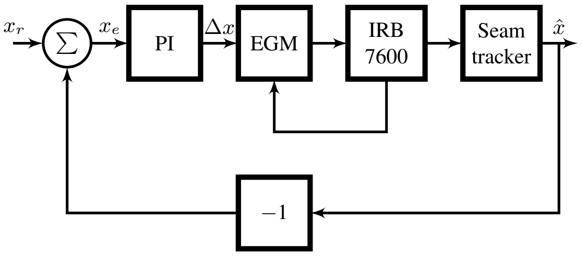

Fig. *6. Block diagram of the position controlled process. The seam tracker and PI controller formed an outer-control loop. An inner loop was formed by the EGM interface and the IRB 7600 robot system.*

3.3 Control design

Prior to welding, a nominal trajectory along the seam had to be defined. To initiate welding, a search motion was performed by the robot, that moved the tool towards the work-piece at the beginning of the seam. This motion was monitored by the robot's internal sensors only. Once contact was established, the FSW was performed. Force-sensor feedback was used for force control in the z-direction, while velocity control was used in the y-direction. In this phase, significant error in the position determined by the forward kinematics of the robot was expected, as large contact forces and torques acted on the tool. Therefore, feedback from the laser seam tracker was used to adjust the movement of the tool in the x-direction, possibly yielding small deviations from the nominal trajectory.

For each time step, the seam tracker measurements indicated the position of the tool in relation to the seam in the x-direction. This measured relative position at time step t is denoted $\hat{x}^t$. Further, the reference is denoted x_r^t. A PI-controller was used to determine a position reference change Δx^t to send to EGM. The controller determined the error x_e^t, and then the output Δx^t, according to

$$x_e^t = x_r^t - \hat{x}^t \tag{3}$$

$$\Delta x^t = K_p x_e^t + x_i^t, \tag{4}$$

where K_p is the proportional gain, K_i is the integral gain, and x_i is the integrated error which is updated as

$$x_i^{t+1} = x_i^t + K_i x_e^t h, \tag{5}$$

where h is the sample period. In turn, EGM sent reference values to the low-level robot joint controller. The position regulator hence took the form of a cascade controller, with the EGM system as inner controller and the PI controller described above as the outer. This is illustrated in the block diagram in Fig. 6.

4. Experimental Setup

The robot used in the experiments was the ABB IRB 7600 [13] robot arm. The following two experiments were performed:

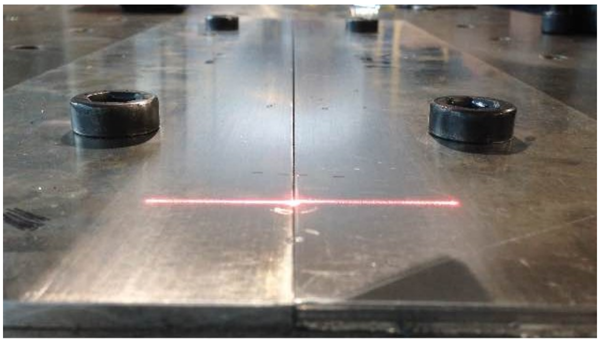

Fig. *7. Work-piece with straight seam prior to welding. Also visible is the laser beam for seam tracking.*

- Experiment A: A straight seam of 5 cm was welded. There was no significant initial position error. The welding duration was 5 s.
- Experiment B: A straight seam with the length of 10 cm was welded. Initially, the tool was purposely positioned with 0.5 mm offset to the seam, in order to excite the control loop. The welding duration was 10 s.

The work-pieces before welding looked similar for both experiments. That for Experiment B is shown in Fig. 7.

In both cases, the work-piece material consisted of 3 mm thick aluminium alloys, and the welding was based on the stationary-shoulder FSW technique. The tool was oriented such that it was almost perpendicular to the work-piece, although with a 1° tilt angle towards the trailing edge of the tool, in order to provide additional forging force onto the plasticized material. This orientation was kept constant. To ensure satisfactory mechanical properties of the welded material, the tool was required to be within 0.5 mm from the center line of the seam. The laser seam tracker measurements were used for evaluation of the system performance.

The laser seam tracker measurements must be accurate enough to determine whether the required accuracy of the tool position was achieved. For example, white measurement noise would propagate directly to the evaluation data, indicating larger position variance than was actually the case. Moreover, a constant measurement error would not be seen in the evaluation data, because the controller would drive the tool to a corresponding offset, while driving the measured control error to 0. The position measurement accuracy of the sensor was ± 0.1 mm, and therefore, measurements with at least this margin to the maximum allowed deviation indicate satisfactory tool position.

5. Results

The relative position of the seam, as measured by the seam tracker, is shown in Figs. 8 and 9. The signal was kept within the required accuracy of 0.5 mm, in both experiments. The resulting weld from Experiment B is shown in Fig. 10, and for Experiment A, it looked similar.

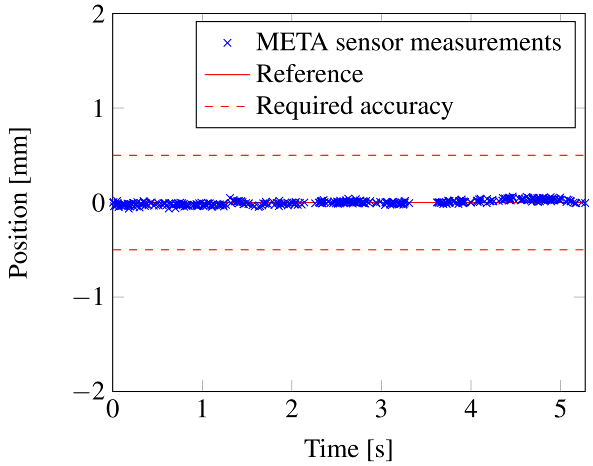

Fig. 8. Seam tracker measurements while welding the straight seam. The controller kept the measured signal within the required accuracy of 0.5 mm. Some severe outliers occurred. These were removed automatically before the controller acted on them, and are not shown here.

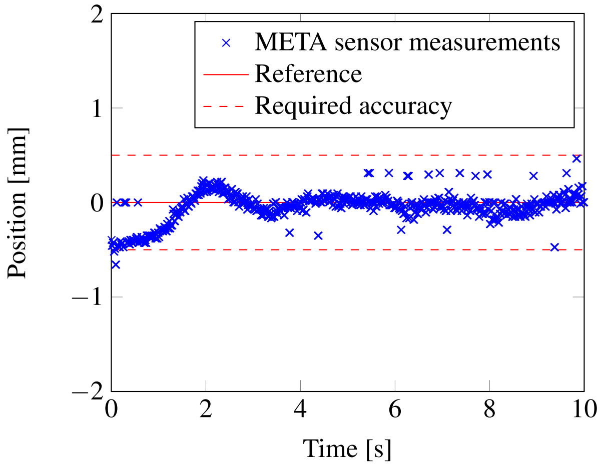

Fig. 9. Seam tracker measurements while welding the straight seam, with an initial step response. The controller kept the measured signal within the required accuracy of 0.5 mm. Again, severe outliers occurred. These were removed automatically before the controller acted on them, and are not shown here. However, what seems to be less severe outliers can be seen.

6. Discussion

The results implied that the required accuracy was achieved. In Fig. 8 the measurements seem to follow the reference very closely. However, there was an interval after 3 s where no position measurements were obtained. A probable cause was that the seam tracker obtained ambiguous measurements from the laser reflections, which, in turn, leaves room for improvement. Nevertheless, a visual inspection of the resulting weld showed that the tool had not deviated notably from the seam within this interval.

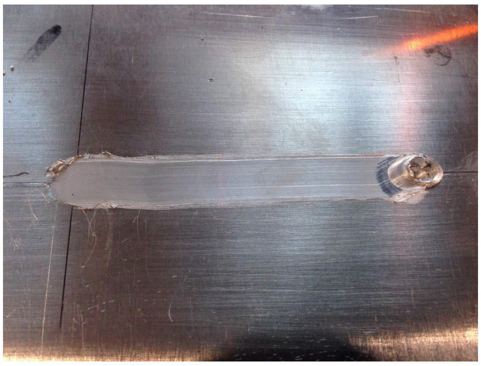

Fig. 10. Resulting straight weld. The laser sensor tracked the seam, providing relative position measurements as feedfback for the controller.

More deviations from the reference appeared in Fig. 9. In the transient part, this was because the initial position was purposely erroneous, in order to excite the controller. There were also more outliers as compared to Fig. 8. This was most likely due to small differences in the seams, such that the seam in Experiment A was more likely to be successfully detected.

For evaluation, it would be better to use yet another external sensor for position measurements, providing ground truth. Ideally, this sensor should be more accurate than the the laser seam tracker. For example, an optical tracking system could be used. However, such a system was not available in this project setting.

The configuration of the mirror must be known for the position estimation. Further, irregularities in the mirror plane would affect the estimation performance. However, no such issue was significant in the experiments performed.

Albeit many of the implementation aspects presented here would vary for different robot cells, the principles of the position control and laser seam tracker usage would generalize well to other robotic FSW arrangements.

Alternative configurations for implementing custom algorithms were possible. Simpler algorithms could be implemented in a native robotic language such as the ABB RAPID language. This would suffer the potential drawback of not being powerful enough for computationally demanding algorithms.

Implementing algorithms on a standard PC gave several benefits. More common programming languages such as C, Python and Matlab could be used, and it facilitated both hardware and software changes.

Dividing the logging and algorithms into two separate parts allowed for easier implementation and reduced code dependence of programs. Another advantage was that errors in logging implementation did not affect the controller software. Maintenance of logging software and server could be done independently of experiments. It also allowed for connection of several robot cells to a single server.

7. Future Work

The next step in this work is to verify the method on seams that are not straight, e.g., curved seams. Further, the robot cell had one external axis, which enabled welding of circular seams. Welding of such seams were tested briefly, with promising results, but it remains as future work to verify the method in this context more rigorously.

Similarly, trials with a floating-bobbin FSW tool, commonly used for applications where the weld is difficult to support by a backing bar such as hollow extruded profiles, have shown interesting initial results with the method described here. However, a complete and formal evaluation of this usage is left as future work.

In the work presented here, the tool pose was adjusted only in one dimension, perpendicularly to the seam. It remains as future work to make corrections also along the seam, as well as in orientation. In this context, multimodal, non-Gaussian probability distributions of the state based on measurement data are expected. For this purpose, a particle filter algorithm for 6D pose estimation was developed. It was based on input from the robot joint encoders, the laser seam tracker and a 6D force/torque sensor, and was verified in simulations. However, it remains as future work to integrate this state estimation algorithm into the real system, and verify it experimentally.

8. Conclusions

In this work, we addressed the question whether a robot could be used for FSW with sufficient accuracy, by compensating for high deflections due to large contact forces. External position measurements were obtained from a laser seam tracker, and deviations from the seam were compensated for by feedback of the measurements to a position controller. The requirement on the position accuracy was fulfilled. The principles described here generalize well to other robot cells.

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