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# Robot-like MIG Welding Machines for Large Steel Structures

**Abstract:** Weld volume, geometry and quality standards in structures in the wind energy sector demand automation. Conventional industrial robots are often infeasible due to safety factors, cost, work space available and the time-consuming programming involved. On the other hand, typical machining tasks such as cutting, arc welding, and ultrasonic testing are so complex that they cannot be mechanised using simple appliances. Small, inexpensive modular machines on rails, known as crawlers, bridge the gap between simple mechanised equipment on the one hand, and industrial robots on the other. They inherit the easy handling and versatility for use even in difficult site conditions from the former, together with the possibility of programming and sensor-controlled movement from industrial robots. The article discusses the possibilities and limitations in this concept by reference to a series of examples from applications.

**Keywords:** robotisation, MIG welding, large steel structures

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## Introduction

Much of the welding in manufacturing steel products and plant construction is done manually for a variety of reasons, including small batch numbers, poor accessibility, three-dimensional seams, complex programming and prevailing working and environmental conditions. Currently, seams running in three-dimensional paths are almost exclusively manually welded.

Small automated robot-like structures attached to mainly ferromagnetic components using magnets provide an almost ideal solution. Combining CNC-like programmability with sensor-based seam tracking, camera monitoring and manual path correction by joystick makes operation easier while significantly increasing deposition rates and reproducible weld quality and greatly improving working conditions for welders [1, 2].

## State of the art in appliance technology

Recent years have seen a modular movement system on rails emerge [3] to bridge the gap between simple mechanised welding tractors and industrial robots. The authors introduced the colloquial term *crawler*, and the allusion to (giant) insects was indeed intended.

The system consists of three basic components:
- the guide rail
- various movement modules for tool positioning and orientation
- the accompanying control technology

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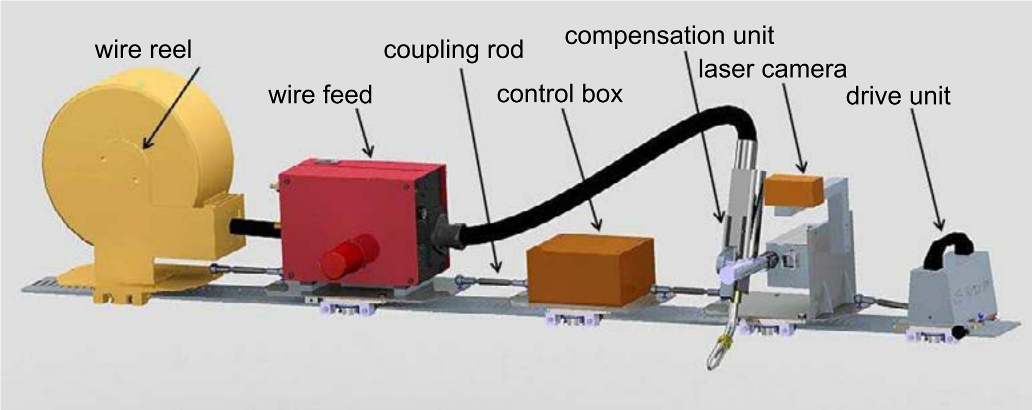


Fig. 1. Welding tractor diagram

The *guide rail* itself is fixed and can withstand relatively heavy loads, but also allows for a tight curvature radius. The rail consists of monolithic laser-cut elements fixed to brackets and magnets or suction cups attached to the surface of the component.

The *movement modules* are small, light and inexpensive, and each has just one function to make it easy to operate and service – no module weighs more than 10 kg. Customers select from a variety of modules according to application, and can expand on and add to the modular system as needed. Modules are coupled in serial as they are on a normal railway, and connect up to form a "train". In the simplest case, a train will have a tractor unit, control box and balancing unit. More complex tasks or very long seams have seen wire reel and feed modules each on its own chassis prove highly successful (Fig.1).

A computer-based control system is necessary in any event, but should be viewed under the conditions of a welding shop. The environmental conditions are rough, and so is the treatment of the machine. Robustness, compactness, simple and intuitive operation, easy replacement of components in the event of an accident, as few cable connections as possible and preferably wireless data transfer play an essential role in this environment, and absolutely require acceptance among welders.

Hardware miniaturisation and tumbling hardware prices, the convergence of control, computer and communication technology in the development towards *IoT* (Internet of things) and the increasing influence of computer games in our daily lives play a role in raising acceptance while opening up intriguing new possibilities. It takes unconventional ideas as well as the right software to create completely new products or product features.

## Selected applications

### *Welding on an oversized tubular structure*

A **tripod** is a type of offshore wind turbine foundation designed as a tubular structure consisting of 10 tubes ranging between 2,500 and 6,000 mm in diameter and a typical metal thickness of around 60 mm (Fig. 2). Three pedestals are each connected to the central tube by a head and foot socket. Connecting the three head sockets alone requires about a tonne of welded material – ideal for welding mechanisation and automation.

Welding tests were performed on a specially designed test rig both on site and in the workshop. A three-dimensional rail was mounted to the head socket connection to guide the crawler in a climbing position along the weld (Fig. 3 and 4).

Fig. 2. Dimensional proportions of a tripod crawler based on a CAD model

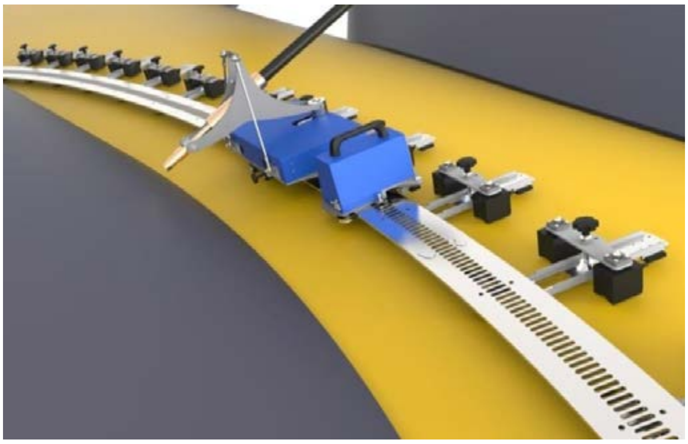

Fig. 3. CAD model of the rail-guided system

Fig. 4. Testing on the test rig

### *Approach*

The application centres on the control system. A Beckhoff® PC control system suitable for almost limitless extension, upgrading and customisation was used on the tripod. This system results in relatively high costs. All of the relevant information and interaction options for the user are available on the manual control panel. With the welder's assistance and camera process visualisation, a manual welder becomes the process controller and optimiser working without requiring head and hand protection in comfortable conditions offsite.

Sensor tracking using a 2D laser scanner from Micro-Epsilon Messtechnik GmbH & Co. KG makes fully automated welding possible. The welding data is collected after each stringer bead without requiring an arc. The geometric data of the joint is recorded, stored and visualised at a gap of 10 mm (Fig. 5).

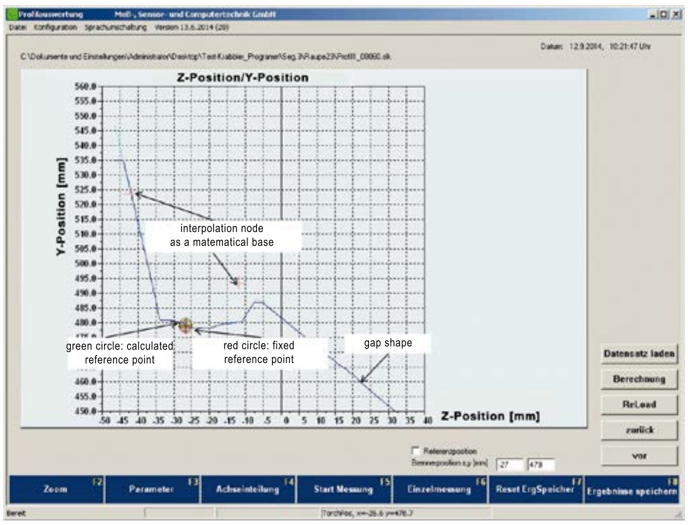


Fig. 5. Measurement software with visualisation

### *Welding tests*

The actual geometrical and welding conditions at the head socket connection were simulated on a test rig. Figure 6 shows the test rig with complete welding equipment for welding segments in positions PF and PF045.

Fig. 6. Tube segment clamped in positions PF and PF045

### *Test procedure*

A **seam opening angle** of 45° was selected to match the actual component. Different bevel angles result from the variable position of the weld against adjacent components.

The welding process parameters on the base metal, S355G10+M, were determined on small scarf-joint samples at bevel angles of 10°, 20° and 30°. These samples were tack welded for a seam opening angle of 45° and strengthened using reinforcement plates, then placed in a welding position matching that of the actual component, and welded. The tube segments

Table 1. Welding process parameters (PF045 position)

| **Additional material** | Stein Megafil 821 R; Diameter 1.2 mm; DIN EN ISO 17632-A: T 50 6 1Ni P M 1 H5 | | | | |
|---|---|---|---|---|---|
| **Inert gas** | DIN EN ISO 14175 – M21 – ArC – 18 | | | | |
| **Position** | **Stringer bead** | **Current *I* [A]** | **Voltage *U* [V]** | **Wire feed $v_D$ [m/min]** | **Welding speed $v_S$ [cm/min]** |
| WL | - | 120–130 | 17–17.5 | 3.2 | 20 |
| 1–5 | 1–11 | 210–230 | 26–26.5 | 7.0 | 32 |
| 6–15 | 12–50 | 260–270 | 26–26.5 | 8.7 | 40 |
| DL | 51–57 | 260–270 | 26–26.5 | 8.7 | 40 |

were cut from the sheet metal and rolled into shape in exactly the same way as with actual components [4].

Using preliminary welding instructions for reference, corresponding segments were welded by preheating the components using an autogenous flame at 100-120°c and welded together using the stringer-bead technique with around 55-65 stringer beads.

Table 1 shows an example of the additional material used, inert gas, and welding process parameters documented by measurement. The operator manually held the tool at angles varying between 20° and 40° due to the accessibility and design of the layered structure. Welding instructions were then prepared for three welding positions.

Fig. 7. Multi-layer weld

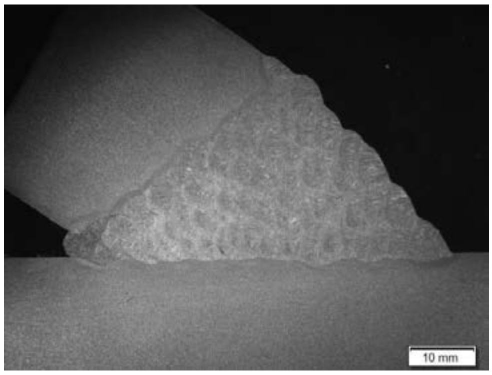


Fig. 8. Bevel-groove weld macrosection from the welding position

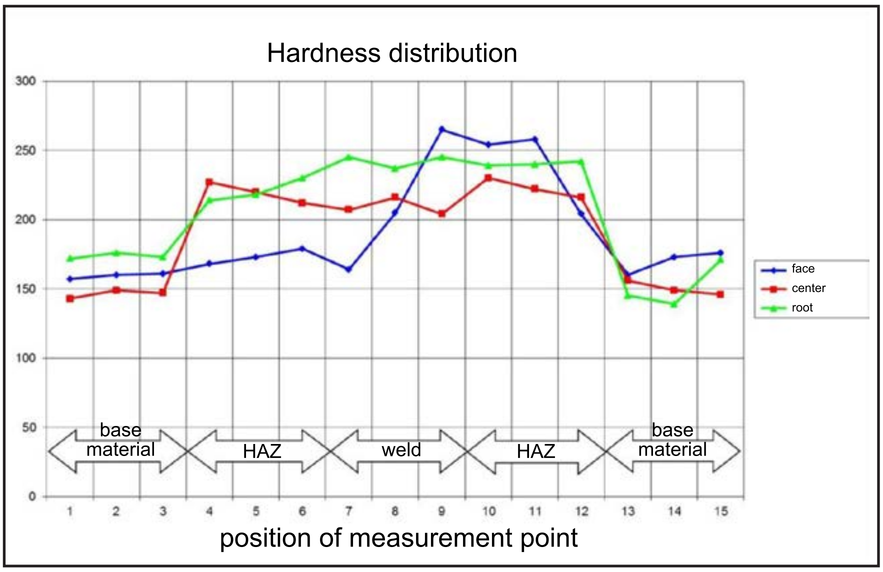


Fig. 9. Result for the hardness measurement at HV10

### *Results*

Figure 7 shows the production status of the weld, and Figure 8 shows the associated macrosection. The evaluation did not reveal any irregularities. The impact energy values obtained lay between 55 and 192 J. Hardness measurements according to Vickers were performed on two macrosections at each welding position. Figure 9 shows an example for the above sample.

### ***Door frames in wind-tower segments***

The access door at the foot of a wind tower constitutes a weak point in the cylinder cross-section that needs to be compensated for using a thick-walled door frame by cutting into the tower segment along the frame's cross section, preparing a welded seam and sealing the frame in using a butt weld. Both subtasks:

– cutting out the frame form using autogenic torch cutting and
– preparing a test-safe butt weld between the frame and tube segment involved developing technical solutions using a crawler.

### *Cutting the opening for the frame*

Serving as a jig, the frame is pushed into the tube segment in the six o'clock position. The guide rail guide for the crawler manufactured using a CAD model of the frame is attached to the frame. The crawler is a "real" CNC machine controlled by an NC program generated using TubeCut® [5], which TubeCut® previously calculated using a DXF file of the frame shape together with the diameter and metal thickness of the tube section as input parameters in a matter of seconds.

The frame has relatively large manufacturing tolerances by nature, requiring sensor compensation on two axes. The sensors are based on the two component surfaces to couple together, that is, the frame and the length of the tube section. Smooth operation requires a gap of at least 100 mm between the internal cutting flame and the measurement point of the sensor (which operates using red light). Passing the sensor information on to the NC program for offline operation requires a high degree of mathematical complexity due to the three-dimensional shape of the intersectional contour, and this requires sensor information to be connected on each NC block online. Even so, this was successfully achieved using Linux and a wholly FOSS-based control system on a single-board computer (BeagleBone®). Conventional control systems from large, global manufacturers could of course be used as well, but they would raise the costs many times over and require more space to work.

The sectional contour needs to be preheated. A combined cutting and preheating tool saves space and tubing, providing a tried and trusted solution. Maximum process reliability is required, re-tapping into the contour leaves notches that need to be sanded and refinished in a complex process. This means that the technical maximum cutting speed is not reached and the propane fuel gas flow is kept to around 200 mm/min. Including all of the additional work involved, cutting the section will take a maximum of 180 minutes at a margin for error of around ±3 mm (Fig. 10), the cutting time itself taking up around 45-60 min.

Fig. 10. Door frame-tube jacket combination with guide rail mounted

### *Welding in the frames*

Welding the frames in obviously also involves the crawler. In this application, the crawler works as a "fake" CNC machine as the welding path has been generated online as the sum of sensor and offset parameters using control inputs (such as pendulum parameters). Welders are explicitly integrated into the process as their knowledge and experience are essential in monitoring and controlling the process by camera and remote control (Fig. 11).

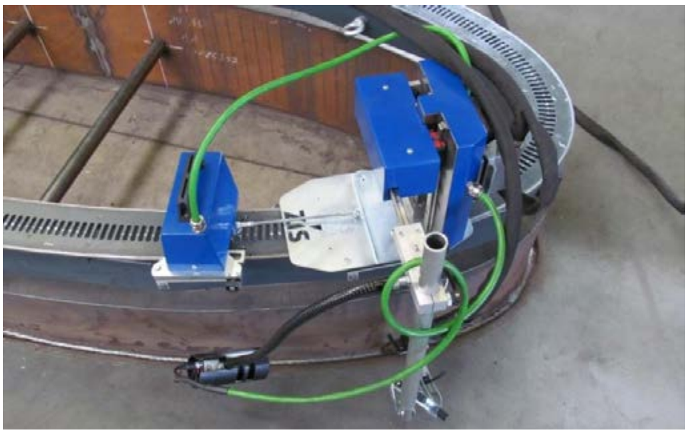

Fig. 11. System on rails for welding in door frames

Unlike the cutting process, the hardware remains largely unchanged apart from replacing distance sensors with a monitoring camera. Both are equipped with quick-change systems for replacement in a matter of minutes. The technology can be adapted using the software running on the control computer.

Several systems are used by customers in multi-shift operation, and generate the desired economy of scale by combining significantly reduced production times in reproducible quality with a significant improvement in working conditions for welders.

### *Welding tubular joints for jacketed offshore foundation structures*

At the time of writing, welding smaller tube joints is still a thing of the future. “Small” refers to a socket diameter of around 400 mm. Each jacket has a larger number of identical joints, making a cost-effective process all the more important.

Considerations have progressed towards creating more small-scale crawler solutions to take investment costs into account at the same time as the system and technology design using industrial robots was being developed. The socket is fixed to the main tube, and the rail is arranged as a collar around the socket and magnetically fastened to the main tube. This keeps the socket and rail attached to one another within a coordinate system, with the rail geometry controlling most of the main movement. The crawler is only responsible for compensating for tolerances as well as tool orientation and guidance along the z-axis (Fig. 12).

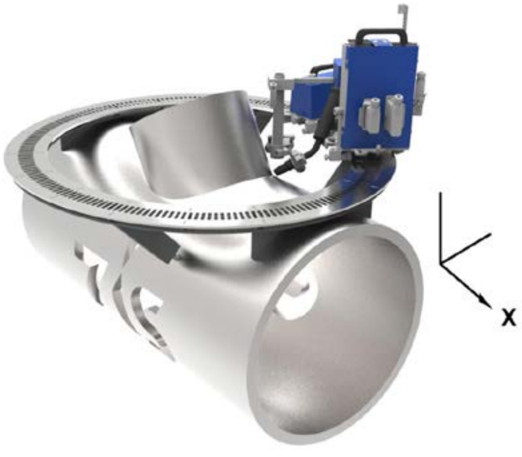


Fig. 12. CAD model of a system on a rail for welding tube and socket connections

Main tube positioning and movement make it possible to keep a flat position while welding. The NC program together with the rail system as a complete DXF file for laser cutting are again (almost) fully automatically generated using TubeCut®.

### Summary and outlook

The applications of a welding tractor on rails demonstrate the possibility of mechanised multi-layer welding on curved three-dimensional multi-layer welded seams. Both the process remote-controlled by a welder using camera monitoring on the molten bath and fully automated sensor control have been tested, and are feasible. It takes a brief training session for a capable qualified welder to be able to operate this equipment as a matter of routine. The technical solution is protected by a patent cluster.

Sensor-based welding does not take any significant additional time compared to manual welding correction by joystick, but it does involve significant time savings compared to familiar teach-in programming in industrial robots.

Apart from eliminating the physically and mentally strenuous activity otherwise involved and generating a constant, reproducible level of weld quality compared to manual welding, significantly increased deposition rates are possible at 1.5 kg/h minimum – many times the deposition rates that can be achieved by manual welding [6]. Welding efficiency is reflected in time savings of at least 50%. Using the equipment described also easily ensures compliance with the mechanical engineering quality standards placed on welded seams in offshore steel structures.

Major advances in control technology are to be expected in the future with intensive efforts dedicated to alternative operation and process monitoring concepts. Attempts using game controllers have been devised to this end and tested on different groups of people [7].

In addition, intensive efforts are being undertaken to enable smartphones to be used as control computers and as control and monitoring devices. These may not be industrial-grade solutions as yet, but it is becoming apparent that this particular exercise would greatly appeal to the younger generation and may help to attract new groups of people to a career in welding.

## References


[1] *Mechanisiertes Schweißen komplizierter Konturen in Zwangsposition an großvolumigen Bauteilen [Mechanised welding on complicated paths in positions other than flat on large-volume components]*. SLV Halle GmbH; Final Report 2011, Reg. No.: MF090183

[2] *Zerstörungsfreie Prüfung dreidimensional gekrümmter Schweißverbindungen mit veränderlicher Nahtflanken [Non-destructive testing on three-dimensional curved welds with variable weld edges]*. SLV Halle GmbH; Final Report 2014, Reg. No.: VF120013

[3] European patent EP 2384842 B1, 2013: *Equipment for creating welded seams along spatial paths on intersection curves that may deflect along the plane in very heavy tubular truss-like structures*

[4] Müglitz, J.; Weise, S.; Herrmann, J.; Mückenheim, U.; Büscher, K.A.: *Tubular based support structures for offshore wind turbines*. 15th International Symposium on Tubular Structures, Rio de Janeiro, 2015, Proceedings, CRC Press/Balkema Boca Raton, London, New York, Leiden, 2015 http://dx.doi.org/10.1201/b18410-38

[5] *TubeCut® parametric tube-cutting software*, ZIS Industrietechnik GmbH, Meerane, 2016

[6] Löffler, T.: *Schweißtechnische Erprobung von schienengeführten, roboterähnlichen Maschinen mit 3D-torsionsgekrümmten Schnittkonturen [Welding tests on robot-like equipment on rails with 3D torsion-curved contours*], BSc thesis. Mittweida University of Applied Sciences, 2013

[7] Weise, S.; Ströfer, M.; Müglitz, J.: *Schienengeführte, roboterähnliche Maschinen zum Schweißen, Schneiden und Prüfen. Schweißen in der maritimen Technik und im Ingenieurbau [Robot-like equipment on rails for welding, cutting and testing. Welding in maritime and construction engineering*], 14th conference, Hamburg, 15-16 April 2014