Robotic Arc Welding — Trends and Developments for Higher Autonomy

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Abstract

The development of robotized welding is truly impressive and is today one of the major application areas for industrial robots. The first industrial robots was introduced in the early 1960's for material transfer and machine tending. Not long after that, robots was used for spot welding and in the early 1970's for arc welding as well. During the years, significant developments have taken place both concerning the robot equipment and the welding equipment to meet the different challenges within the application area. This paper describes the development and progress of robotization in welding over the years and also some projections and trends for the near future in this field.

1 Developments in robotic welding

1.1 The early years

Research and development work on industrial robots goes back to the 1950's when developments took place in the field of NC machine tools. These machines had many building blocks in common with robots and the first prototype of an industrial robot from Unimation saw the day of light in 1960, and was in operation at Ford in 1961. The robots at the time was relatively simple with so called Point To Point (PTP) control and was primarily used in materials handling and machine tending with spot welding coming shortly after. Still in the 1960's, Trallfa (now ABB Robotics) developed a robot for spray painting. The concept of programming and control of such a robot was quite different. The principle was that the programmer grabbed the robot end-effector and moved it in space and time while the robot recorded the motions. Typically, many such programs with quite short cycle times were made in a short time and the best one was selected for production. The method turned out to be a practical solution for the application in mind. It was tested on other applications as well in the 1970's, including arc welding, but with less success.

Most robots used at this time had hydraulic drives but demands from applications such as arc welding put a pressure to develop electric drive robots. In 1973, ASEA (now ABB Robotics) presented an all electric robot that shortly after that successfully was used in arc welding (6 kg payload) and spot welding (60 kg payload). Still, the motion control was rather simple and to overcome problems to generate straight line movements, a synchronized PTP control was used so that all axes stop at the same time for a defined motion.

Trajectory generation of the welding torch in Cartesian coordinates was a major problem to solve to be able to use robots in arc welding more efficient. Robots had to be able to produce jerk-free motions in 3D space that can be defined according to common practice of using geometrical shapes in product design, i.e. linear and circular movements. At the time, however, the controllers did not have the necessary computing power to achieve this and the work around procedure was to define points along the weld joint. Depending on the necessary accuracy the distance between such points could vary, but in general there were about 30-40 mm between the points. The travel speed was defined by the time to travel between two points. For spot welding, the interpolation of a path was not so important as developments for robust and light spot welding guns. Other important issues was related to fast and accurate communication between the robot controller and the welding power source and supporting peripheral such as automatic cleaning systems for the spot welding electrodes.

From mid 1970's a number of different robot applications was under constant testing and evaluation including deburring, polishing, gluing, cleaning of castings, and so on. Such work included development of peripheral equipment for use in robotic stations as well and integration of these to the robot controller.

In the area of robotic arc welding, servo controlled positioners were introduced with integrated motions of both the robot and the positioner. However, this integration was, and still is, in general limited to joint space of the robot and the positioner as opposed to a real integration from a welding point of view where a relative motion of a welding torch along a weld joint (the object to be welded) is the actual requirement. Definition of such integrated motions require a world model as normally used in modern systems for simulation and off-line programming of robots. The introduction of positioners increased the use of the robot in many ways: objects could be oriented for better accessibility of the robot and better orientation of the weld that increases productivity and/or quality. Moreover, robots was mounted on moving tracks, usually a gantry with the robot hanging upside down. This increased not only the working space but also the complexity of the system. Products started to be designed for robotic welding taking advantage of the new technology by improvements in quality and productivity. Another important issue was soon to get a solution: how to decrease the usually long set up time between different products. Ideas based on the FMS (Flexible Manufacturing System) principle guided the design of new welding systems with automatic loading and unloading of fixtures on the positioner. This was further developed during the 1980's.

1.2 Computer controlled robots

The next phase started around 1980 when new controllers introduced Continuous Path (CP) control. This resulted in better performance in general, but the most important aspect was that the user could define the robot motion in different coordinate systems, for example Cartesian coordinates. This was possible due to the improved computing power that allowed kinematics models of the robots to be implemented in the controller based on fairly, at the time, complex computational demands.

The general developments in mechanics, drive systems, computers and electronics has added to performance and complexity, and large arc welding systems with gantries and positioners started to be common. Welding

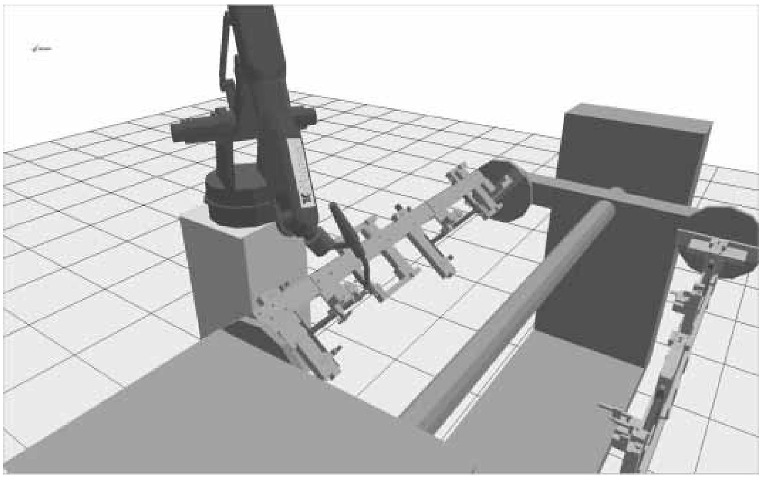

Figure 1: *Example of robot station with double positioner.*

systems with one or several robots on one gantry and one or several positioners were introduced. Robotic systems for arc welding was demanding and included in general a large number of integrated servo controlled motions.

At the end of 1980's, the use of off-line programming started to be something that not only was available in robotics laboratories. The concept was developed from general principles of programming and NC code preparation using APT (Automatically Programmed Tool). However, programming a robot is quite different than programming an NC machine. There are great differences in kinematic structure, number of motions, accuracy, logics and flow of operations, etc. Thus, much research has been devoted to this area over the years. During the 1970's and early 1980's off-line programming was mainly based on textual information. As CAD/CAM systems and computing power developed, research in the area of off-line programming looked at possibilities to integrate these technologies in the research. Examples of companies that started in the mid 1980's in this area are Technomatix and Deneb (now Delmia), that now are the leading companies in developing software products for simulation and off-line programming of robots. Figures 1 and 2 show robot welding stations with positioner and gantry modeled in a simulation system.

1.3 Developments during the 1990's

Finally, looking back ten years from now, are there any news in robotics during the 1990's up till now? Without going too deep in the mat-

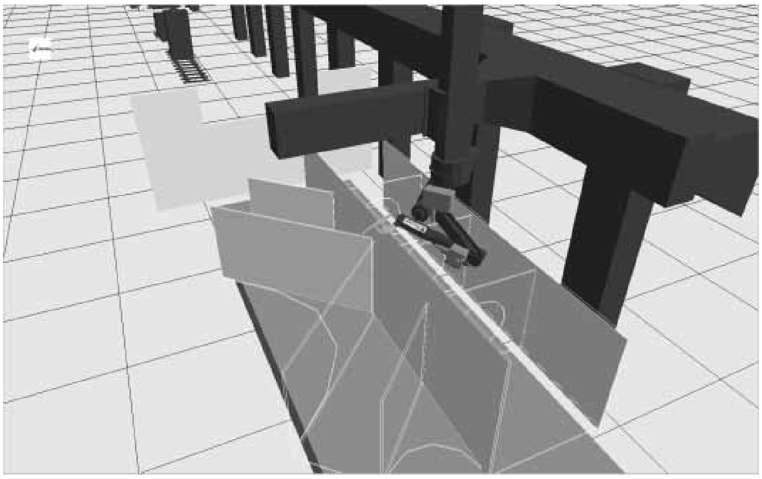

Figure 2: *Example of robot station with gantry.*

ter, most technological advancements seen today could be predicted ten years from now with basically more robustness and better performance/functionality in all subsystems such as controllers, manipulator including drive system, sensors (2D vision becoming cheap and easy to use and laser triangulation seamtrackers for arc welding is more robust to use, although still quite expensive) and integration of systems with standardization of components. However, a challenging new technology was introduced in industry, although developed in the 1980's, namely simulation and off-line programming. This technique allows object oriented programming and manipulation[1] and detailed analysis of robot tasks provides a platform for optimization of robot operations not possible by other methods. It is also an important tool in analysis of robot structures in general. It was gradually introduced in the automotive industry i the early 1990's and is today a truly profitable, although still expensive, tool to get more out of a robot station investment.

Concerning welding, power sources have in general much more advanced control systems that allow better performance concerning productivity and quality than before. New processes are emerging on a larger scale and some examples are "rapid arc" principles with more than double welding speed in arc welding using a longer stick-out, and laser welding with solid state lasers as an highly interesting possibility for robotic use where mirrors and fiber optics will be obsolete.

To sum up, the developments in industrial robots area can now offer truly reliable solutions in most standard automation problems. The new

[1]Please note that the term object oriented programming refers to objects in the world model and not the same term used in computer science.

challenges touch the area of low series down to one-off production where the problems not only is at the robot but how to produce a product at all, to control and run processes, machines, peripherals, where demand from the market must be met through instant ramp-up .

2 Technological challenges related to robotic welding

Arc welding and spot welding was one of the early process applications applied by robots and welding is still a major application process for industrial robots. The main difference between the two welding processes with respect to the robot performing the process is the manipulation. While a spot welding robot only has to move to a precise location, an arc welding robot also must fulfill accurate continuous path operation of the end-effector during welding. Additional peripheral equipment such as multi-axis positioners have been added to the normal arc welding station giving multi-axis robot stations. Such welding robots work quite well in series production today where the welding process and workpieces can be optimized within narrow tolerances.

However, when moving to a more flexible production, arc welding turns out to be a complex process with many interrelated parameters, sometimes counteracting with each other and related to many activities in the production of welded structures including design, materials selection, welding process selection and welding process parameters. It is in this context important to view the robotic welding station as one integrated unit, where the optimization of controllable parameters must be taken from a holistic point of view.

Within the near future, other welding processes will develop to be used in greater numbers than today. An example of such a process is laser which can be used as a complement to both arc welding and spot welding. With the introduction of solid state lasers, new ways to integrate the laser system to the robot is in sight in the very near future and new opportunities will come up including welding new materials that are not suitable with traditional welding methods. However, the use of lasers for welding put new requirements on the robot, specifically concerning motions where the laser welding process can be produced at a much faster speed than conventional arc welding. It also put greater demands on accuracy than traditional welding methods.

An important issue related to robotic welding is the large number of interrelated parameters to obtain the results defined in productivity and quality terms. In traditional robotic welding, product volume is large enough to allow try-outs but with the decreased volumes in combination with short product life cycle, application processes must be integrated to robots to allow an integrated control for fulfillment of issues that count: productivity and quality.

Moving from large volumes to low volumes with less try outs will in general increase the use of sensors. Sensors is a way to cope with accuracy problems in general and for arc welding they are used for tracking the weld joint, locating the weld joint (start/stop) and process control of the welding power source parameters. Along with the developments of sensors for arc welding the controllers have incorporated functionality to use the sensor information. However, looking more closely at this the use of sensor information is not that impressive as it should be. In general, seam tracking is done with position only. The reason is obvious; a change of the position within a limited range does not usually produce problems related to joint limits or singularities of the robot arm. However, if the robot follows the weld joint by changing both the position and the orientation, such problems is likely to occur even if the position change is small, within 10 mm, as a minor change in orientation will produce large effects on the robot joint positions. Figure 3 a close up view is shown from a typical welding case to illustrate the issues described above. The wrong selection of position parameters (orientation or position of gantry axes) can jeopardize the welding task. Likewise, a small change of orientation may cause collision with the workpiece in narrow sections.

The requirements for such functionality are twofold:

1. A more advanced seam tracking system will decrease resources needed for programming. In the general case, this will allow the sensor to guide the robot from start to end with only a small number of intermediate poses in case of complex weld joint. Naturally, the sensor guidance must include orientation as well as this is an important parameter to obtain defined quality and productivity.

2. In cases where the sensor detects a change or orientation of the weld joint, the welding torch must be oriented in a specific angle relative the joint to produce the weld in accordance with the welding specification procedure. This procedure defines the conditions to comply with quality requirements and the torch orientation is as many other parameters an important parameters to control.

Moreover, joint limits and singularities are not only a problem related to sensors. A common case in robot arc welding is to produce long welds. When the weld gets longer, it will be more difficult to select a proper starting configuration of the robot so it can produce the weld move without

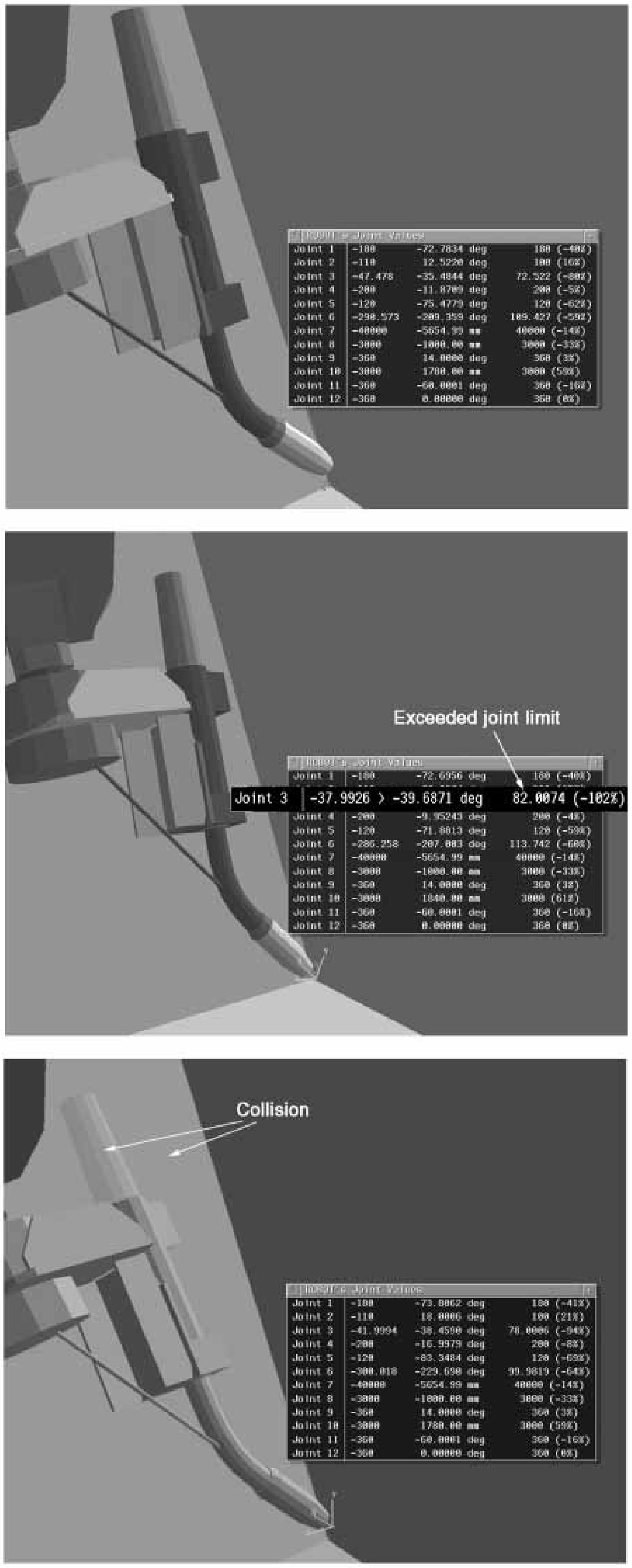

Figure 3: *Close up view of a welding case. Above: nominal position. Middle: exceeded joints due to bad selection of gantry axis no. 10. Below: collision with work piece due to orientation of the torch along the weld wire.*

ending up in joint limits. When this happens the robot stops or change configuration which means usually to rotate the wrist axes so sit can proceed with the motion. There are however solutions to this problem: as the welding torch is symmetrical along the torch direction a rotation around this axis can be done without disturbing the quality. This may seem good but in the same way an orientation may produce side effects as joint limits and singularities it may also produce unwanted movements of the other parts of the robot. During welding the robot moves close to the work piece and even very small movements may produce collisions.

As indicated, single problems in arc welding can be tackled with today's technology and what is needed it to apply a holistic point of view in integrating all tools available to get an integrated system for fulfilling the task defined by the product and the welding procedure specification. This integration means to raise the abstraction level to a world model as can be shown in simulation systems for robots. Access to the world model gives the system a possibility to address all issues described above and during real time react and control the robot in an error recovery mode for fulfilling the task.

The majority of industrial robots have 6 degrees of freedom. Many typical robot applications on the other hand require only 5 degrees of freedom, including arc and spot-wlding. The extra degree of freedom available can be used to choose an infinite number of kinematic robot configurations that all will fulfill the given task; the system is redundant. This is also the case when positioners and gantry is used. The robot controllers of today does not take advantage of this and the robot operator is responsible to choose one of the configuration which he/she thinks is the best suited for the given situation. The robot controller (or the general simulation system during off-line programming) does not give any feedback if this is the optimal one. The operator has to trust his/her intuition or experience with the system to choose the best one. The non-linear structure of a robot arm with revolute joints makes it difficult to predict possible problems with singularities, exceeded joint limits and tangled cables. Especially when sensor control is utilized and the state of the system during execution can vary.

It is hard to fully utilize the potential of robot simulation system when sensors are used. The condition of the system is not fully known in advance and the sensors are used to handle deviations. The complexity of the system makes it difficult to predict all the problems that could arise during execution in the physical world. Industry copes with this problem basically by avoiding sensors which has the consequence of lower system flexibility, although the complexity of the system is reduced at the same time. The approach to make full use of simulation systems and sensors in robotic welding could be twofold:

- During off-line preparation of the task, software tools should be available to perform a sensitivity analyze. Possible problems like near collisions, joint-limits or kinematic singularity should be paid attention to and suggestions to improvements should be proposed to increase the robustness. Models of the process, robot and sensors are used to be able to really resemble the complexity of the real world.
- During on-line execution continuous supervision of the system is performed. Requests to models of the process, robot and other active devices in the workcell are made in real-time in order to optimize quality and handle limitations. A continuous update of a world model enable a correct action to any emerged situation. Problems like near collisions, joint-limits or kinematic singularity can be handled on-line but only if an updated world model is accessible. Typically would a change of torch orientation in order to avoid singularity cause collisions with any other object in the workcell.

The object model of the virtual world should enable easy programming, reuse and maintenance of the robot tasks. The possibility to link any attributes and methods to the different objects to increase the knowledge base of the virtual world to more than a geometrical description.

3 Future Trends

Robot systems for automation of welding is today a robust technology that combines productivity with quality in a variety of designs of the robot stations. The technology is combined with a set of supporting techniques related to welding engineering (different processes, control of the welding process, etc.), sensor technology and simulation and programming.

New welding processes such as rapid arc and laser welding will put further demands on control aspects on robot systems as the travel speed increases and process operating parameters becomes more narrow. The use of new production processes is however linked to product design and the preparation of robust programs for the welding station so that the benefits of new processes can be utilized to its optimum.

The present trend in robotic welding system is to further increase the system's flexibility. One such example is the use of robot systems in welding large structures in areas such as ships, bridges and earth moving equipment, etc. Within these areas, the number of work pieces of each type is relatively small, sometimes down to one and high volume products in the range of a thousand. To a large extent, this is a reality today and there are attempts to take this further into one-off production. With the increased use of sofisticated 3D CAD/CAM systems and combining the information with robot simulation systems, this trend will be a reality within a few years to come. Already at this stage, there are industrial adapted systems that in an economical way produce parts in one-off production, but in such cases the products are defined by parameters and programming is in such cases fairly straighforward. The general case is much more demanding since it has to cover issues related to parameters of the welding process and robot related issues related to joint limits and singularities of the kinematics of the manipulator. In this context, simulation is an extremely important tool that will develop further in the coming years. In summary,

- More complex work pieces and weld cases can be simulated, programmed and tested as there is no principle restriction in work piece geometry.
- Simulation, testing and programming can be done using a virtual model of the work piece before it exist providing short lead time in preparing the production.
- Design of weld jigs can be done including testing without the need for a physical mock-up.
- Programs are in general more consistent where part of programs can be reused. Better documentation and reuse of data gives in general better quality of the programs.
- The programming method provides a safe way to produce programs. This is of importance in complex industrial robotic systems including those with integrated gantry systems, servo tracks and positioners. Manual on-line programming should otherwise force the programmer to work within the system which, especially in complex systems, demand great resources both with respect to personnel safety and the machine system.

Moreover, simulation systems and off-line programming provide the necessary tools to address issues related to generation of robust programs. In a first phase software tools must be developed to optimize the robot program considering both the robot and the welding process. In the second phase we can expect a coupling between a simulator with the

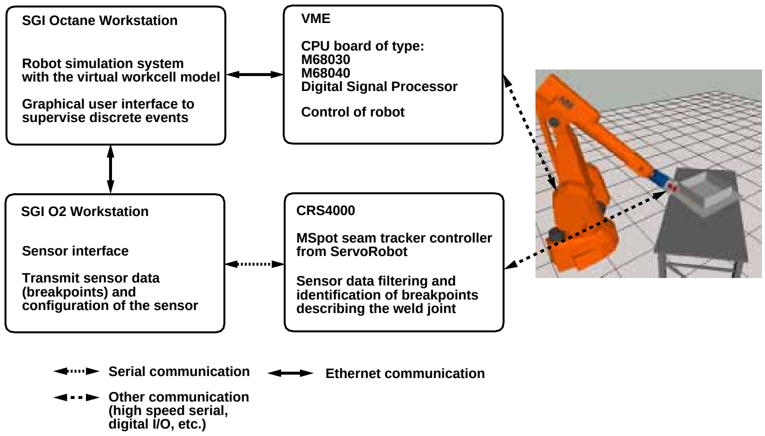

Figure 4: *Laboratory set-up with an industrial robot, connection with a laser triangulation seam tracker and world model control (robot simulator).*

world model of the robot station and the robot controller. Robot status and various sensor information will provide important data to alert the controller if something is going wrong. In such case the concept of a world model can be used for generating programming instructions online as a method for error recovery. Such coupling is illustrated in figure 4 where an industrial robot is hooked up to a simulation system in a laboratory environment. This type of connection can be used in several ways and one possibility is, as discussed above to close the loop concerning sensor data to the simulator which holds information about the world model. Through this coupling, on-line analysis can be made concerning issues related to joint limits, singularities and collisions and error recovery can take place before such problems happen by taking over the control from the robot program in the robot controller. Note that such a connection is possible with today's robot controllers by using a "Remote Procedure Call" (rpc) where an external process (control systems) sends robot native instructions in real time. It may not be realistic to have one expensive robot simulator for one robot. Instead, the high level as represented by the simulator is not expected to take control during normal execution and in such cases a high level controller may be connected to tens of robots in a real implementation.

4 Concluding remarks

To sum up, the developments in robot technology for welding has provided industry with robust technology that meet most requirements. This is shown by the great proportion of robots used within the welding application area. However, new developments are on the way that will increase the autonomy in performing the welding task. This may not be important in today's robotized welding but with shorter product series, quicker ramp-up of production volume and a general trend to be more flexible to meet demands from the market, new demands on more autonomous robots will come as well. This will certainly address issues described in this paper with an emphasis on integrating the various specialized techniques in control (joint limits, singularities, redundant systems), programming, simulation, sensors and last but not least the welding process as specified in a welding procedure specification. With such an integrated control scheme much more can be done not only concerning autonomy but also to raise productivity and quality.