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Robotic Welding Technology

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Abstract

Since the first industrial robots were introduced in the early 1960s, the development of robotized welding has been truly remarkable and is today one of the major application areas for industrial robots. Robot welding is mainly concerned with the use of mechanized programmable tools, known as robots, which completely automate a welding process by both performing the weld and handling the part. Robots are quite versatile and hence have been used for a variety of welding types such as resistance welding and arc welding. This paper describes the development and progress of robotization in welding over the years and also discusses many advantages and disadvantages entangled with the use of different robotic welding technologies.

Key words: Arc welding, Automatic welding, Friction stir welding, Robotics, Robot welding, Spot welding, Welding.

1. Introduction

Probably, no other technique has been and still is more important to the durability, easement, and development of humankind than welding. It is an essential process in building our world in different aspects including, agriculture through the manufacture of tillers, tractors, and combines; food processing through production of crushers, cookers, and conveyors; mining through manufacture of drills, excavators, and trams; transportation through the production of trucks, trains, ships, cars, buses, and planes; security maintenance by manufacture of tanks, missiles, and submarines; power generation and transmission; information communication; and hundreds of other applications [1].

Welding is a technology that provides the fastest, strongest, and most economical method of joining metals. The field of welding has moved from coal-fired furnaces and hammers used for forging iron, to modern methods such as the concentrated accelerated free electrons of the electron beam process and the advantages of robots and lasers. Welding had its ancient origins in the fires of blacksmiths, who could forge two white-hot pieces of metal together with hammer blows and patience [2].

Preliminary, the simple definition of welding was “joining metals through heating them to a molten state and fusing them together.” With increasing progress in welding processes and techniques, the definition has had to change. It is quite true to say that the weld is stronger than the base metal. Beside the classic application areas of welding such as shipbuilding, automobile manufacturing, building construction, and pipelines, currently welding techniques are being used in more complex application fields including aircraft, space vehicles, and nuclear reactors.

Conventionally, arc welding and oxyacetylene fuel welding were two main welding techniques but currently more modern technologies are being used such as pulsed GTAW, plasma welding and cutting, submerged arc, pulsed GMAW, and electron beam and laser welding. Basically, there are two types of welding namely, fusion and non-fusion. The former is the most common and involves the actual melting of the parent metals being joined. Non-fusion welding is most commonly represented by soldering and brazing where the parent metal is heated, but not melted, and a second or “filler” metal is melted between them, forming a strong bond when all are cooled [3].

1.1 History of welding

The earliest evidence of welding can be traced back to the Bronze Age. The earliest examples of welding are welded gold boxes belonging to the Bronze Age. The Egyptians also learnt the art of welding. Several of their iron tools were made by welding. During the middle Ages, a set of specialized workmen called blacksmiths came to the fore. Blacksmiths of the middle Ages welded various types of iron tools by hammering. The welding methods remained more or less unchanged until the dawn of the 19th century. In the 19th century, major breakthroughs in welding were made. The use of open flames (acetylene) was an important milestone in the history of welding since open flames allowed the manufacture of intricate metal tools and equipment. Englishman Edmund Davy discovered acetylene in 1836 and acetylene was soon utilized by the welding industry. In 1800, Sir Humphrey Davy invented a battery operated tool which could produce an arc between carbon electrodes. This tool was extensively used in welding metals. In 1881, French scientist Auguste De Meritens succeeded in fusing lead plates by using the heat generated from an arc. Later, Russian scientist Nikolai N. Benardos and his compatriot Stanislaus Olszewski developed an electrode holder for which they secured US and British patents.

During the 1890's, one of the most popular welding methods was carbon arc welding. Around the same time, American C.L. Coffin secured a US patent for metal electrode arc welding. N.G. Slavianoff of Russia used the same principle for casting metals in molds. Coated metal electrode was first introduced in 1900 by Strohmenger. A coating of lime helped the arc to be much more stable. A number of other welding processes were developed during this period. Some of them included seam welding, spot welding, flash butt welding, and projection welding. Stick electrodes became a popular welding tool around this time as well.

After the end of World War I, the American Welding Society was established by Comfort Avery Adams. The aim of the society was the advancement of welding processes. CJ Holstag also invented the alternating current in 1919. However, alternating current was first commercially utilized by the welding industry only in the 1930's.Automatic welding was first introduced in 1920. Invented by P.O. Nobel, automatic welding integrated the use of arc voltage and bare electrode wires. It was used for repairing and molding metals. Several types of electrodes were also developed during this decade.

The New York Navy Yard developed stud welding. Stud welding was increasingly used for the construction industry and also for shipbuilding. It was during this time that the National Tube Company developed a welding process called smothered arc welding. In the sector of shipbuilding, the stud welding process was replaced by the more advanced submerged arc welding. A new type of welding for seamlessly welding aluminum and magnesium was developed in 1941 by Meredith. This patented process came to be known as Heliarc welding. The gas shielded metal arc welding or GTAW was another significant milestone in the history of welding which was developed in Battelle Memorial Institute in 1948.The CO2 welding process popularized by Lyubavskii and Novoshilov in 1953 became a welding process of choice for welding steels, as it was comparatively economical. Soon, electrode wires of smaller diameter were launched. This made welding of thin materials more convenient. There were several advancements in the welding industry during the 1960's. Dual shield and Inner shield welding and Electroslag welding were some of the important welding developments of the decade. Plasma arc welding was also invented by Gage during this time. It was used for metal spraying. The French also developed electron beam welding, which is still used by the aircraft manufacturing industries of the United States.

Some of the recent developments in the welding industry include the friction welding process developed in Russia, and laser welding. Laser was originally developed in Bell Telephone Laboratories but it is now being used for various kinds of welding work. This is due to the inherent capacity of lasers in rendering precision to all kinds of welding jobs. Friction welding, which uses rotational speed and upset pressure to provide friction heat, was developed in the Soviet Union. It is a specialized process and has applications only where a sufficient volume of similar parts is to be welded because of the initial expense for equipment and tooling. This process is called inertia welding.

Laser welding is one of the newest processes. The laser was originally developed at the Bell Telephone Laboratories as a communications device. Because of the tremendous concentration of energy in a small space, it proved to be a powerful heat source. It has been used for cutting metals and nonmetals. Continuous pulse equipment is available. The laser is finding welding applications in automotive metalworking operations. Recently, Magnetic Pulse Welding (MPW) is introduced by Pulsar Ltd. of Israel using capacitive power as a solid state welding process. Discharging 2 million amps in less than 100 microseconds this process can create a metallurgical, a non-metallurgical or a mechanical lock, depending on the substrate involved. No heat affected zone (HAZ) is created since only a rise of 30°C occurs.

There have been more innovations in welding during the last 50 years and with the invention of the laser, using a laser beam to do welding has become popular in automated plants. There have also been many safety improvements as well and the tools, equipment and protective clothing now make welding a very safe activity [4].

1.2 Industrial automation

In the present day global marketplace, manufacturing organizations are facing national as well as international competition, forcing them to further improve their performances. To this effect, the concept of *Computer Integrated Manufacturing* (CIM) have been introduced in various production environments with different purposes including human productivity improvement, product quality improvement, capital resource productivity improvement and providing rapid response to the market demands. The CIM strategy is to integrate the information bases of the various units of automation within the traditional framework of manufacturing. In this respect CIM can be viewed as a closed loop control system where a typical input is the order for a product and the corresponding output is the delivery of the finished product [5].

Automation of the physical production processes on the shop floor is a key component of the CIM strategy for improving productivity. In this context, robots have played an important role in the automation of various operations robots have been successful in automating simple and repetitive operations while simultaneously enhancing the quality of manufactured products in many production areas. The use of robots is also highly desirable in hazardous manufacturing operations such as spray painting, welding, etc., which pose known health risks to human operators.

Industrial robots are essential components of today’s factory and even more of the factory of the future. The demand for the use of robots stems from the potential for flexible, intelligent machines that can perform tasks in a repetitive manner at acceptable cost and quality levels. The most active industry in the application of robots is the automobile industry and there is great interest in applying robots to weld and assembly operations, and material handling. Typical applications of robots include welding, painting, assembly, pick and place (such as packaging, palletizing and SMT), product inspection, and testing; all accomplished with high endurance, speed, and precision.

The most commonly used robot configurations are articulated robots, SCARA robots, Delta robots and Cartesian coordinate robots, (aka gantry robots or x-y-z robots). In the context of general robotics, most types of robots would fall into the category of robotic arms (inherent in the use of the word manipulator in the above-mentioned ISO standard). Robots exhibit varying degrees of autonomy:

- Some robots are programmed to faithfully carry out specific actions over and over again (repetitive actions) without variation and with a high degree of accuracy. These actions are determined by programmed routines that specify the direction, acceleration, velocity, deceleration, and distance of a series of coordinated motions.
- Other robots are much more flexible as to the orientation of the object on which they are operating or even the task that has to be performed on the object itself, which the robot may even need to identify. For example, for more precise guidance, robots often contain machine vision sub-systems acting as their "eyes", linked to powerful computers or controllers. Artificial intelligence, or what passes for it, is becoming an increasingly important factor in the modern industrial robot.

George Devol applied for the first robotics patents in 1954 (granted in 1961). The first company to produce a robot was Unimation, founded by Devol and Joseph F. Engelberger in 1956, and was based on Devol's original patents. Unimation robots were also called programmable transfer machines since their main use at first was to transfer objects from one point to another, less than a dozen feet or so apart. They used hydraulic actuators and were programmed in joint coordinates, i.e. the angles of the various joints were stored during a teaching phase and replayed in operation. They were accurate to within 1/10,000 of an inch[citation needed] (note: although accuracy is not an appropriate measure for robots, usually evaluated in terms of repeatability - see later). Unimation later licensed their technology to Kawasaki Heavy Industries and GKN, manufacturing Unimates in Japan and England respectively. For some time Unimation's only competitor was Cincinnati Milacron Inc. of Ohio. This changed radically in the late 1970s when several big Japanese conglomerates began producing similar industrial robots [6].

In 1969 Victor Scheinman at Stanford University invented the Stanford arm, an all-electric, 6-axis articulated robot designed to permit an arm solution. This allowed it accurately to follow arbitrary paths in space and widened the potential use of the robot to more sophisticated applications such as assembly and welding. Scheinman then designed a second arm for the

MITAI Lab, called the "MIT arm." Scheinman, after receiving a fellowship from Unimation to develop his designs, sold those designs to Unimation who further developed them with support from General Motors and later marketed it as the Programmable Universal Machine for Assembly (PUMA).

Industrial robotics took off quite quickly in Europe, with both ABB Robotics and KUKA Robotics bringing robots to the market in 1973. ABB Robotics (formerly ASEA) introduced IRB 6, among the world's first commercially available all electric micro-processor controlled robot. The first two IRB 6 robots were sold to Magnusson in Sweden for grinding and polishing pipe bends and were installed in production in January 1974. Also in 1973 KUKA Robotics built its first robot, known as FAMULUS, also one of the first articulated robots to have six electromechanically driven axes.

Interest in robotics increased in the late 1970s and many US companies entered the field, including large firms like General Electric, and General Motors (which formed joint venture FANUC Robotics with FANUC LTD of Japan). U.S. startup companies included Automatics and Adept Technology, Inc. At the height of the robot boom in 1984, Unimation was acquired by Westinghouse Electric Corporation for 107 million U.S. dollars. Westinghouse sold Unimation to Stäubli Faverges SCA of France in 1988, which is still making articulated robots for general industrial and cleanroom applications and even bought the robotic division of Bosch in late 2004. Only a few non-Japanese companies ultimately managed to survive in this market, the major ones being: Adept Technology, Stäubli-Unimation, the Swedish-Swiss company ABB Asea Brown Boveri, the German company KUKA Robotics and the Italian company Comau.

1.3 Welding robots

What makes robotics so interesting is that it is a science of ingenious devices, constructed with precision, powered by a permanent power source, and flexible from the programming point of view. That does not mean necessarily open source, but instead the availability of powerful APIs, and de facto standards both for hardware and software, enabling access to system potentialities without limitations. This is particularly necessary on research environments, where a good access to resources is needed in a way to implement and test new ideas. If that is available, then a system integrator (or even a researcher) will not require open source software, at least for the traditional fields of robotics (industrial robot manipulators and mobile robots). In fact, that could also be very difficult to achieve since those fields of robotics have decades of engineering efforts, achieving very good results and reliable machines, which are not easy to match. That open source issue is nevertheless very important for the emerging robotics research (like humanoid robotics, space robotics, robots for medical use, etc.) as a way to spread and accelerate development.

Industrial Robotic Welding is by far the most popular application of robotics worldwide [7]. In fact, there are a huge number of products that require welding operations in their assembly processes. The car industry is probably the most important example, with the spot and MIG/MAG welding operations in the car body workshops of the assembly lines. Nevertheless, there are an increasing number of smaller businesses, client oriented, manufacturing small series or unique products designed for each client. These users require a good and highly automated welding process in a way to respond to client needs in time and with high quality. It is for these companies that the concepts of Agile Production [8, 9] apply the most, obviously supported by flexible manufacturing setups (Figure 1). Despite all this interest, industrial robotic welding evolved slightly and is far from being a solved technological process, at least in a general way. The welding process is complex, difficult to parameterize and to effectively monitor and control [10-14]. In fact, most of the welding techniques are not fully understood, namely the effects on the welding joints, and are used based on empirical models obtained by experience under specific conditions. The effects of the welding process on the welded surfaces are currently not fully known. Welding can in most case (i.e. MIG/MAG welding) impose extremely high temperatures concentrated in small zones. Physically, that makes the material experience extremely high and localized thermal expansion and contraction cycles, which introduce changes in the materials that may affect its mechanical behavior along with plastic deformation [15-17].

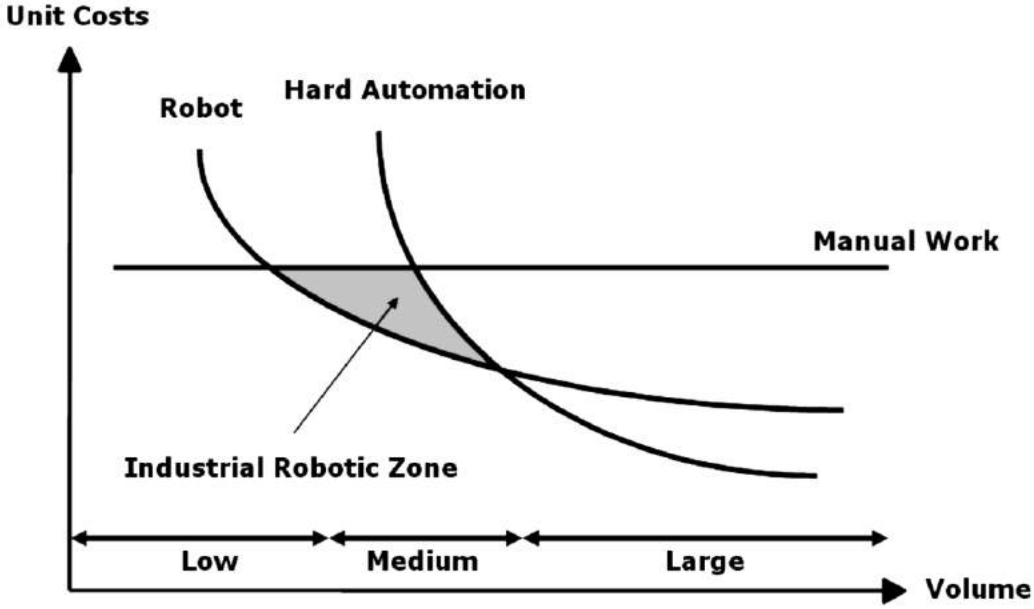


Figure 1. Industrial robot zone

Those changes must be well known in order to minimize the effects. Using robots with welding tasks is not straightforward and has been a subject of various R&D efforts [18-22]. And that is so because the modern world produces a huge variety of products that use welding to assemble some of their parts (Figure 2). If the percentage of welding connections incorporated in the product is big enough, then some kind of automation should be used to perform the welding task. This should lead to cheaper products since productivity and quality can be increased, and production costs and manpower can be decreased [23]. Nevertheless, when a robot is added to a welding setup the problems increase in number and in complexity. Robots are still difficult to use and program by regular operators, have limited remote facilities and programming environments, and are controlled using closed systems and limited software interfaces [24-28].

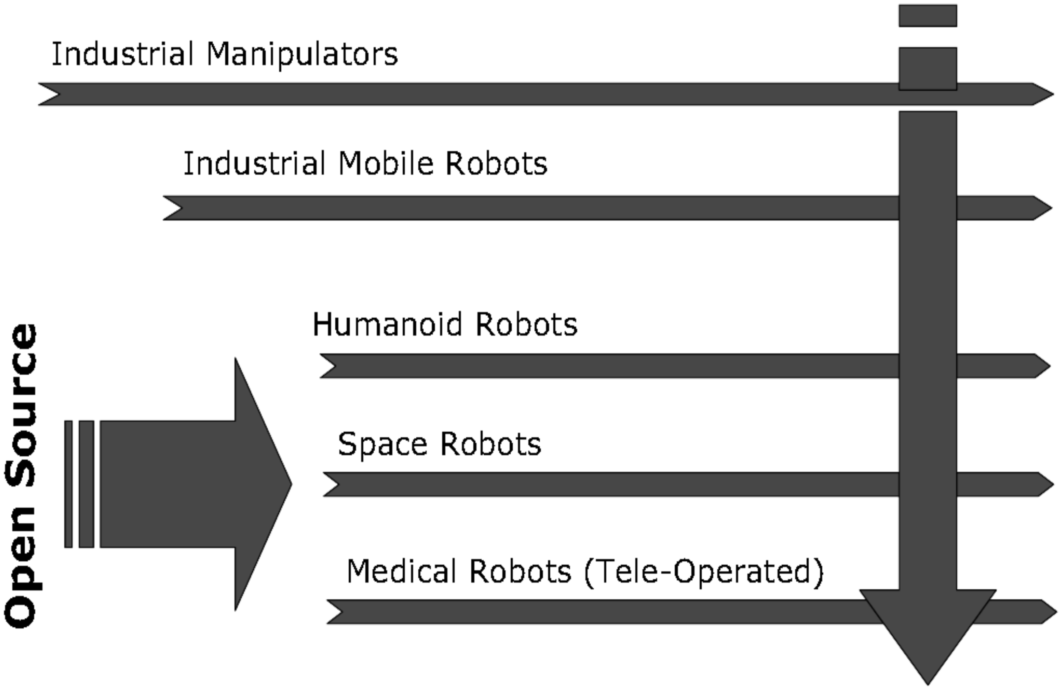


Figure 2. Traditional and modern fields in robotics research

2. Robotics in Welding

2.1 Motivations

Automated welding is no longer just for long-run, large lot applications. New digital technology that links welding equipment and robotics to create easily programmable cells is enhancing its appeal for ever-smaller and more specialized applications. When robotics and welding operations come together on the shop floor, the results can include dramatic improvements in quality, better repeatability, faster production cycles, less downtime, and with all of this, an increase in profits. New options in welding automation are broadening its application and its economic value as a production tool. More flexible programming and finely tuned digital communications between welding power sources, robotic arms and positioning equipment makes it possible to create a system that is economically justifiable and productive for manufacturing operations of almost any size.

The conventional wisdom has been that automated welding only made sense for longer runs of repetitive parts. Historically, the costs of fixturing and special work stations tended to create these limitations. New systems that combine easier programming, more flexible work holding, and cells that provide closer coordination between weld control, robotic motion and work piece positioning promise to make all but the smallest jobs candidates for automation. A company running different batches of 50 or 100 weldments now can gain many of the same benefits as one that is producing hundreds or even thousands of identical assemblies. Larger firms too can benefit by automating their shorter run or more specialized production welding using a “packaged” pre-engineered system that is easily programmed to their changing needs. With strategic alliances between manufacturers of welding equipment, robotics and positioners, even custom cells are often within reach for small-lot applications.

In the past, manufacturers often looked at only their most complex parts as candidates for automation and concluded the investment wasn't economically justifiable. Today, more flexible systems minimize the need for dedicated fixturing and make it easy to switch production from one part to another. The 80/20 rule frequently applies, as eighty percent of a company's production typically represents only 20 percent of its part sizes. The new robotic welding cells make it easier to automate more of these simple, often repetitive jobs and to switch quickly from one to another. The biggest reason to automate is that it makes economic sense. Robotic systems for short to medium run applications are now more affordable than ever. With a lower investment and greater productivity improvements, the return on investment (ROI) is greater than with larger, individually designed welding lines [3].

Consistent quality is another reason to automate. The fewer uncontrolled variables in the process, the higher the quality of the welds and the more uniform they will be. Improved quality levels and faster turnaround times also help to create greater customer satisfaction. In contrast to custom fixtures, the flexible fixturing or workholding incorporated into the newest robotic cells makes it easy to switch back and forth between a variety of different products with little change over time. This also increases productivity and improves ROI. As with many skilled trades, there is a severe shortage of trained welding operators. This situation creates an "automation imperative" in which it makes sense to transfer the skills to the machine and automate as many repetitive tasks as possible. Even when an operator is involved, labor content is lower. In a robotic welding cell, handling and welding occur simultaneously in two zones. While the operator loads and unloads in one zone, the robot welds in the other. Connectivity between the system's components is what makes welding automation different today from just a few years ago. New industrial communication networks now create a continuous loop for feedback and control of the entire process, from office computer to factory floor and back. Digital communications make these systems much faster than analog controls. They provide more throughputs and are more flexible as well. Moreover, it is easy to add parameters without adding more wires. Real time process evaluation and connectivity to the Internet makes it possible to monitor the process without hardwiring the components together, not only on the factory floor but remotely, in a control room or even at a totally different location.

Equipment manufacturers that previously functioned independently are forming more strategic relationships. By pooling their individual knowledge, they are able to design products that work together effectively as systems. A company with welding expertise that joins with a leading robotics manufacturer and a supplier of innovative positioning systems can offer automated welding solutions that are more effective than if a user tried to assemble a work cell independently. Moreover, the manufacturers of complementary equipment are blurring the lines between their individual firms and creating a new synergy as they cooperate on re-engineering each other's products to work together.

Most robotics manufacturers do their major product development overseas, which sometimes makes it more difficult to coordinate the design of a system in which all components communicate effectively with each other. To facilitate this exchange, at least one robotics firm has centered its development of products for the North American market in the U.S. while also maintaining its international resources. This “best of both worlds” approach allows the company to respond more quickly and effectively to local market needs.

2.2 Disadvantages of welding robots

Despite the advantages of using a robotic welder, they also present a few concerns. Robotic welders are expensive to purchase, which means that an average business cannot afford one. They require trained personnel to man and program and can often break down or need repair. Other concerns are that the limited movement of a robotic arm might not allow the robot to weld all necessary places. This means that a human welder will still have to go in and finish the job. If the object needing to be welded has been placed incorrectly, the welding robot will still weld in exactly the same programmed places, so that the welds are "off" or located in the wrong place. Poor programming can also produce inaccurate results. Robots are also limited to only a few types of welding, and many of these take longer to cool or can even weaken metal if not used properly [4].

2.3 Automated welding

Rectilinear robots move in line in any of three axes (X, Y, and Z). In addition to linear movement of the robot along axes there is a wrist attached to the robot to allow rotational movement. This creates a robotic working zone that is box shaped. Articulating robots utilize arms and rotating joints. These robots move like a human arm with a revolving wrist at the end. This creates an irregularly shaped robotic working zone known as the work arc.

There are many factors that need to be considered when setting up a robotic welding facility. Robotic welding needs to be engineered differently than manual welding. Some of the considerations for a robotic welding facility are listed below:

The selected welding programs include start / stop, gas pre flushing, electrode feed and nozzle flushing. Robots have been used about 15 years to weld complete automotive body assembly and sub assembly components. In general equipment for automatic arc welding is designed differently from that used for manual arc welding. Automatic arc welding normally involves high duty cycles, and the welding equipment must able to operate under those conditions. In addition, the equipment components must have the necessary features and controls to interface with the control system. The number of items of any one type to be welded must be high enough to justify automating the process. If the joints are to be welded on a work piece are few, straight and easily accessible, a rack automatic gas metal gas welding (GMAW) gun or gas tungsten arc welding (GTAW) torch may be suitable for key welds.

An automatics gun also can be used in a fixed position or on a curved track for a curved or circular weld such as joining two pieces of pipes or welding a flat base to a cylindrical shape—a task in which a work piece can be rotated past the gun. If parts are normally need adjustment to fit together correctly, or if joints are to be welded, they are too wide or different positions from piece to piece, automating the procedure will be difficult or impossible. The tabletop size robot is used to maximum effect- welding work piece is one side of a revolving jig. Each side of jig also can be revolved to allow access to both sides of work piece. Robots work well for repetitive tasks on similar pieces that involve welds in more than one axis or where access to the piece is difficult. Welding robots are used in two ways in manufacturing – as elements in production line and as stand-alone units for batch production. Few companies move from all manual welding to a completely automated production line, so many people introduce robotic welding with a standalone cell.

At fabrication or welding trade shows, a variety of welding robots can be seen performing complex maneuvers and elegant pirouettes similar to troupe ballet dancers. These displays are designed to demonstrate the speed and flexibility of today's generation of robots. The fact is, dance moves aside, today's robots can handle a wide range of welding applications. Some of the welding operations that can be performed by robots are as follows:

1. Arc welding
2. MIG welding
3. TIG welding
4. Spot welding
5. Stick welding

2.4. Examples of welding robots

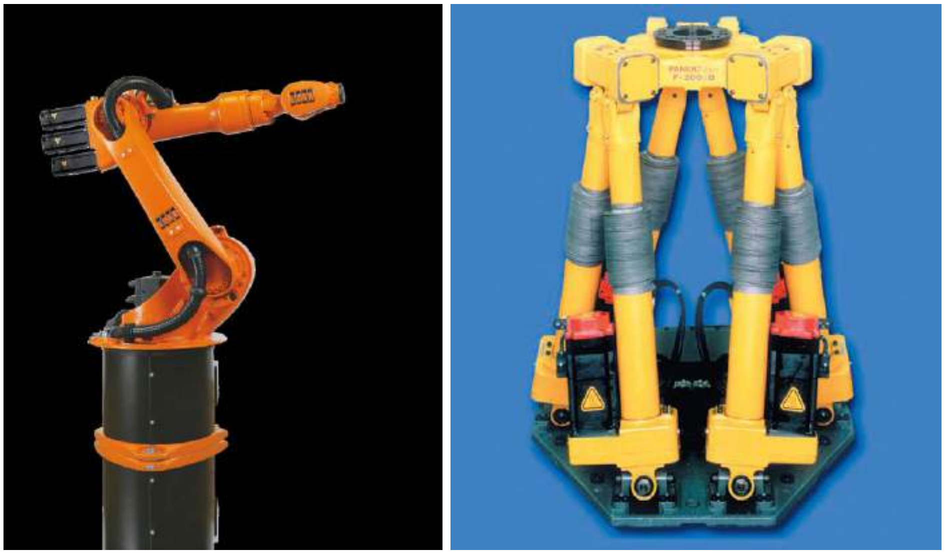
In this section, a few examples of current welding robots are provided.

KUKA:Their versatility and flexibility make the KUKA KR 6-2 and KR 16-2 (Figure 3) our most popular robots. These masterful movers have a payload of 6 or 16 kg and, thanks to their design, are ideal for all space-saving, cost-effective system concepts. That's why they are used virtually everywhere – both in the automotive components industry and in non-automotive sectors. With minimized disruptive contours and a streamlined robot wrist design, these high-precision multi-talents offer outstanding accessibility, even in confined spaces. For cleanroom requirements or environments with a high degree of fouling and high temperatures, the KR 16-2 is also available in the special variants Cleanroom (CR) and Foundry (F) [29].

FANUC:The FANUC F-200iB (Figure 3) is a six degrees of freedom servo-driven parallel link robot designed for use in a variety of manufacturing and automotive assembly processes. The F-200iB is engineered for applications requiring extreme rigidity and exceptional repeatability in a compact, powerful package [30].

Panasonic:Panasonic Perform Arc C Series (Figure 4) are dedicated customized robot systems, made 100% on customer request. Some of the important features of these robots can be summarized as follows [31].

- High quality welding with high production rate
- Torsion-free design for easy transportation with no programming correction, and for program exchanges between the robots for production expansion
- All from one solutions reduce interfaces from different supplies and increase productivity.



(a) (b)

Figure 3. (a) KUKA KR 6-2 robot [29] and (b) FANUC F-200iB robot [30]

Figure 4. Panasonic Perform Arc robot [31]

MOTOMAN:Motoman is extending the success of its arc welding robotic arms with the introduction of the first 7-axis arc welding robot. The flexibility of the VA1400 model (Figure 5) can be used to reduce floor space and achieve higher robot density for increased production. The unique "elbow" axis of the arm also allows the robot to reach around tall parts or reach into boxy parts [32].

CLOOS:Due to the modular product design, the new generation of CLOOS QIROX welding robots (Figure 5) can be optionally equipped with a seventh axis. The off-set axis mounted in the robot base permits horizontal movement of the robot up to 550 mm. The welding of complex work pieces is simplified and accelerated thanks to the considerably increased range. The setting and positioning efforts are considerably reduced because, thanks to the eccentric movement, the welding head can be much easier moved around corners or into niches, for example [33].

Daihen:The Daihen FD-V6 (Figure 5) is suitable for virtually all MIG, MAG, CO2, and TIG welding applications, and Air Plasma Cutting applications. The FD-V6 may be used for common materials such as mild steel, stainless steel, aluminum, titanium, as well as other exotic metals [34].


(a) (b) (c)

Figure 5. (a) MOTOMAN VA1400 robotic arm [32], (b) CLOOS QIROX welding robots [33] and (c) The Daihen FD-V6 robot [34]

3. Robotics in Different Welding Techniques

3.1Spot welding

Spot welding is widely used among the automotive industries as the efficient joining of metal sheets [35]. Classify under the resistance welding, spot welding acts by generating heats with use of a high current, approximately about 1000A – 100,000 A. The welding guns are the main part of the welding. It comes with 2 different kinds but the important is these guns do similar function as to make a close loop circuit, connecting the power supply to the weld spot (Figure 6).

The current passing through the sheet metals as two guns clamps simultaneously. The high current provided will cause the surfaces contact with the electrodes tend to melting. After the energy reach the sufficient level, a weld nugget will start to form. The surfaces, (surfaces between the sheets where having the highest resistance) are heating the surface to be at solid-liquid temperature and forming a molten weld pool [36]. The weld spot which is so called the Heat Affected Zone (HAZ) is cooling down via the thermal condition, where the heat is transferred to the gun which is cooled by cooling water that flows through it. The gun is then open to complete the process. The advantages of the spot welding are that this method uses an efficient energy which is supplied by electrical power supply and generates high current through the generator. This method consume less time for heating the materials. Plus with time for changeovers of material, this method has less lead time than other method and produces high production rates. In addition, spot welding is easy for automation due to the simple construction and yet it no required of filler materials.

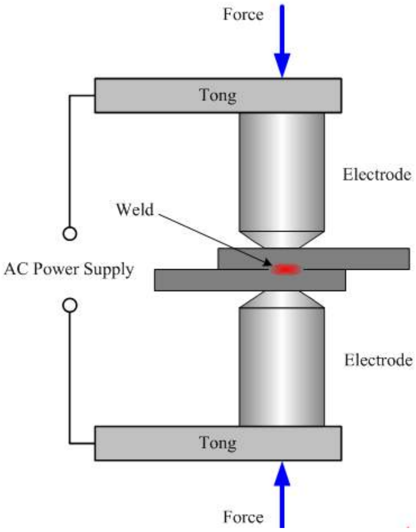


Figure 6. Process of spot welding

The commonly used equipment in spot welding can be divided into two main categories; welding equipment and robotize equipment. The main equipment in robotic spot welding is the spot welding robot in order to have the spot welding to be automated. This robot is available in various sizes which is classify according to how much is the maximum load the robot can manipulate, how far the robot can reach for welding and number of axes can the robot to work on. The welding gun is attached to the end effector of the robot. It is designed to fit the assembly process which come in 2 types; C-type, which is to be the cheaper than X-type. These gun are operated by means of pneumatic actuator which is provide uniform electrode force and hydraulic actuation which is often used when high pressure is needed at a small or limited space (Figure 7). However, technology allows people to discover better solution for problems. A new servo gun was invented which adopt servo motor to operate the gun [37]. This gun has more accurate electrode force control compared to pneumatic gun [38].

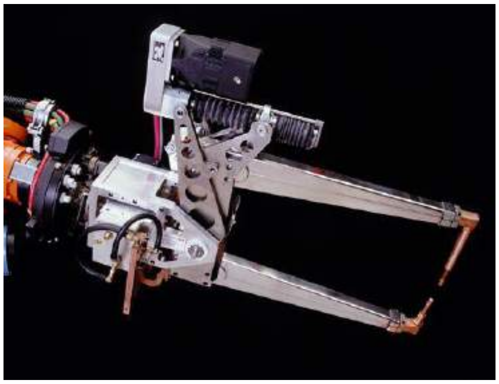


Figure 7. C-type welding gun

Basically, welding gun applies appropriate pressure and current at the welding spot. This means the gun will be exposed to heat and pressure that will cause deformation of the welding electrodes. Automatic tip dresser is used to sharpen the electrode (Figure 8). This is due to soft electrode material, high welding current and pressure. The dressing is done after each working cycle which takes about 1 to 2 second. But to maintain the good contact surface of the electrode is important yet it is define how good the quality of the welding is. In addition, maintaining proper electrode geometry can reduce the production downtime and utility cost. One main problem encountered during the welding process usually is the cables and hoses which are tend to cause limitation of robot movement. Swivel is used to provide compressed air, cooling water, current and signal within single rotating unit.

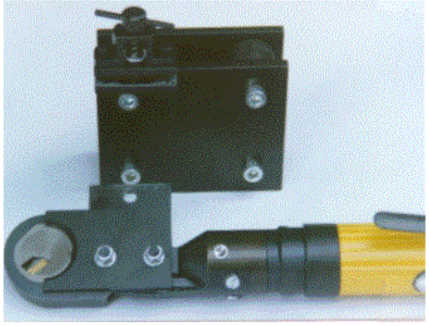


Figure 8. Tip dresser

Swivel greatly improves the efficiency installation of robotic welding (Figure 9). It maximizes the utilization of access to spot-weld areas. It fits directly onto the robot's end effector without any hoses or cables and ensures the quality of the spot weld to be the highest. An automated spot welding need to initiate and time the duration of current. A spot weld timer is used to control welding time when spot welding, and the current as well as sequence and time of other parts of the welding cycle.

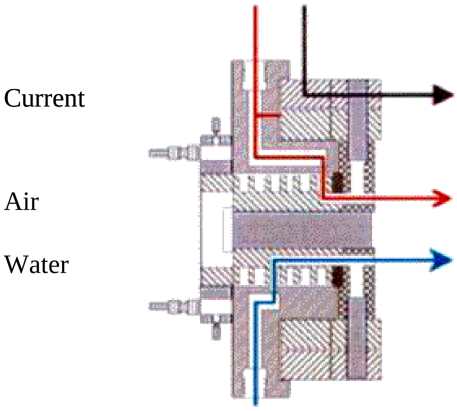


Figure 9. Swivel

As other methods of welding, this method of welding also has numbers of parameter need to be considered during the welding process. It is important to have the optimum control of welding parameters to obtain the satisfactory result of the nugget formation, thus, defining the level of quality of the welding itself. Spot welding parameters includes the electro force, the diameter of the electrode contact surface, squeeze time, weld time, hold time and the weld current. Minor adjustment in any of parameters will influence all other parameters. The diameter of the electrode contact surface has a strong relationship with the electrode force. Lai et al.[37] have carried out a research to estimate electrode face diameter based on servo gun. Servo gun has more accurate electrode force control. It softly touches the sheet metal that will reduce impact and improve the electrode lifetime. In their research, a mathematical model was established to estimate the face diameter. It shows that increase in welding current and force will increase the electrode wear rate and this causing the electrode to be smaller in diameter [37]. As the sheet metals are given force by the electrodes, the electrodes are squeezing. It is the interval between the initial of force applied and the current supplied. This is necessary to ensure the force has reached the desired level before the weld current reaching overload. This is to prevent spatter from occurring as it will cause the electrode and the sheets to get stuck together.

Welding process take place soon after the squeezed time and the current is applied through the sheets. The weld time should be as short as possible. This is the time when the nugget is formed and gets bigger. This can define the strength of the weld. Aslanlar et al. [39] carried out a research to observe welding time effect to welding joints strength. The welding time of 12 and 15 periods give the optimum tensile shear strength at welding current 10kA and welding time of 10 periods give optimum peel strength at welding current of 11kA. This is because the time enough for the nugget grows to its optimum size. It should be at least 20% and not exceeding 80% of the sheet thickness.

Holding time is the time when after welding process, the electrodes are still clamping the sheets with the force applied. This is to cool down the weld and allow the nugget to solidify and join both sheets. The condition meets the principle of heat transfer. As water cools down the electrode, heats from the weld spot are transferred to the cool area to achieve thermal equivalent. This interval time should not too long as the weld could become brittle. However, longer hold time is recommended whenever galvanized carbon steel is used.

Another parameter that significantly influenced the welding is the weld current. This one seems to be the main thing in the process. It is controlled by the setting of the transformer tap switch and the percent of current control. Use of correct current amount also defines the strength of the weld joint. Aslanlar et al. [40] studied the influence of welding current on welding joint strength and found that optimal tensile shear strength and tensile peel strength is attained at 10kA and 11kA of welding current respectively. The current should be keep as low as possible. Spatter will occur as the current reach the overload amount.

It is agreed that technologies bring us high living cost for future but at the same time, it helps people in their living. There are great advantages that give benefits when implementing robotic spot welding. Increasing in production volume and reducing manufacturing lead time but at the same time the quality of product can be improved. In fact, it shows the best production cost obtained compared to manual work in small or medium batch manufacturing [41]. Common application of spot welding is in manufacturing nickel-cadmium batteries, welding metal sheets in automotive industries, and even in orthodontist's clinic, which is used to resize metal 'molar bands'. As its main purpose is to join metals, welding process is mostly used in assembly process worldwide. It is a complex and difficult to parameterize and to monitor and control effectively. However, the effects on the joint are not fully understood and are experienced under specific condition [42].

The main area of research when it comes to automation is the robotic, sensor technology, control systems and the artificial intelligence. All these are to be control by the main component called controller, which is act as a 'brain' to the robot. The controller is used to program the robot, giving an order to the robot to activate sensors, move and activate welding gun to perform a task. Most of the failures in implementing robot are from the software that controls the robot. Many researchers are doing research on problems to perform well-defined task by the controller. Problems occurred are not only on the physical movement of the robot, it might affect the quality of the welding itself. Algorithm is created which provide step-by-step process that is used to solve the problems. Lee et al. [43] found that the quality of current resistance spot welding process is poor with high expulsion rate. He comes out with neuro-fuzzy algorithm in order to reduce the percentage of specimen error and hence increase the welding quality. His research resulted that the neuro-fuzzy inference system is an appropriate technique in monitoring the quality of spot welding process. Too long of weld duration and current will decrease the tensile strength because of too much melting. One main thing the controller does is to control the welding parameter and monitor it to maintain the consistency of parameters magnitude during the welding process take place. Jou [44] has investigated the effect of changeable parameters to output signal for variety of steels in automotive industry. He found that extremely high current yield excessive nugget and led to molten metal expulsion that can cause unpredictable effect. Increase in current supply will also increase the rate of joule heating.

Another approach used to solve problem is using the artificial neural networks. It is a mathematical model which is used to model complex relationship between inputs and outputs or to find patterns in data. This has been used by Martin et al. [45] to explain about a neural network system that is capable of interpreting ultrasonic oscillograms obtained by pulse echo method. It is able to classify the unused input vectors in training as 10 components vector are used to describe ultrasonic oscillograms. Cho [46] in his research to explain a system which is capable of evaluates the quality of resistance spot welding by using dynamic resistance pattern. He found that the Hopfield is established as welding quality estimation system using pattern recognition method. This system is suitable for industrial environment. Neural network produces the best results in strength and nugget diameter estimation. The measurement must be made when current rate of change equal to zero to avoid the inductive noise.

3.2 Arc welding

Father of robotics, George Charles Devol has created the first industrial robots in 1954 [47]. Industrial robot continued to evolve and is directly influenced by the development of computer and massive production demand. At this time, development of arc welding robot in terms of design, control system and sensing ability are seen among engineers as potential areas because it will give highly positive impact to the whole production. Design is in general defined as the establishment of a new algorithm wherein mathematical equation describes the physical parameters setup of the robot [48]. The most important part in arc welding process is the arc itself. Welding process consists of two types of control system which are manual control and automatic control [48]. There are a lot of differences between using automatic control and manual control in welding process that influence primary things such as in product quality level, number of production, error occurrences, hazardous working environment and total production costs.

Another important consideration in improving arc welding robot system is sensing ability. Sensor that is integrated in the central welding system will convert the information from parameters involved into quantitative data such as digital signal, voltage and current [48].

An example of automated welding process is the work done by Lima and Bracarens [49] that used structure for electrode voltage decrement in order to detect temperature change during the process. As a result, the decided value of arc voltage for the welding process becomes more accurate. Creating control for right torch angle is also the important factor in ensuring high quality welding. The study by Silva et al. [50] has established a parallel structure robot where their axes are independent to each other. Therefore if any defect happened at particular axis, it would not influence the other axes, avoiding unnecessary use of high accuracy actuator. Damages will not spread to other axes, resulting in lower maintenance cost. Previously, some researchers such as Rubinovitz and Wysk [51] used offline programming system in his experiment that improves productivity and efficiency of welding process. The total time needed for online programming tasks is reduced because the process of defining specific points is eliminated. The system also lowers the buildup costs of the robot programming system.

By providing new opportunities for welding technologies, the applications of mobile robot have increased rapidly because it can replace human workers for tasks in hazardous working environment. Lee et al. [52] designed mobile welding robot with optimization based on workspace, which is 13% lighter than original design as shown in Figure 10. Moreover, this robot is beneficial when it comes to building shipyard structures. However, design efficiency is lessened for about 4.9%. Chang et al. [53] have developed a method for mobile welding robot in detecting seam and plotting the 3D configuration of the profile. It is tested by using straight line butt welding. The robot is also robust since it can work accurately with unpredictable profiles and rough bead surfaces. Tung et al. [54] explained in their paper image guided mobile robotic system that is capable of producing higher quality welding compare to manual work by experienced workers. After recognizing the defect part, robot will move to the intended welding path. Welding path is achieved by using newly introduced algorithm.

On the other side, Karadeniz et al. [55] observed the influence of welding parameters on welding penetration. Generally, higher welding current and arc voltage lead to higher penetration depth. Welding current has stronger effect on penetration compared to arc voltage and welding speed. Control of weld shape is also important to ensure that welding process meet the requirement specification [56] has introduced a new reinforcement model which functions as feedback element. The system can also be integrated with teach and playback robot in order to control welding current and wire feed rate. Apart from weld shape, uniform cross-section of bead profile is essential in maintaining product quality. Bead profile forming is also critical for surface quality improvement. Therefore, optimal model in creating bead profile is an essential requirement in arc welding. Xiong et al. [57] found that shape of bead profile is highly affected by ratio of wire feed rate to welding speed. Using best model in single bead section, perfect smooth surface is achieved by determining the centre distance of adjacent beads.

Figure 10. RRX4 Mobile Welding Robot

Control system in robotic arc welding is categorized in two; open-loop system and closed-loop system. Open loop system is the basic concept of any control system in welding process, while closed-loop system is the improved system. There are optimal control, adaptive control, and intelligent control. For instance, the work done by Daeinabi and Teshnehlab [58] that developed an appropriate algorithm for controlling arc welding process in terms of seam tracking. Using the algorithm, robots are able to perform good quality welding at any point and it can work in hazardous environment. Formerly, Murakami et al. [59] found that fuzzy logic controller reduce the vibration in tracking locus by using weld-line tracking control. Another important factor affect product quality is bead width. Xue et al. [60] has introduced fuzzy regression system that is capable of maintaining welding quality by applying linear regression model together within the fuzzy variable of the triangular membership functions. The system produces accurate measures for bead width. Sayyaadi and Eftekharian [61] in their work established the application of SCARA robot in GMAW. Combinations of various methods are used in controlling the system such as feedback linearization, neural network, and fuzzy controller, resulting in improvement in system efficiency. Earlier, there is finding of intelligence robotics system named ROBOEDIT [62], an expert system specifically for floor adjustment. The programming assistant is very efficient and result in increase of the number of production. The system is also capable of interpreting NC robot programming and English-like format.

Dung et al. [63] introduced an adaptive nonlinear controller that improves wheel mobile robot detecting ability as shown in Figure 11. The system is powerful and hardly affected by disturbances from outside. Multivariable control introduced by Huissoon et al. [64] contains an empirical state space model. It has the ability to identify reference steps and produce fair disturbance rejection.

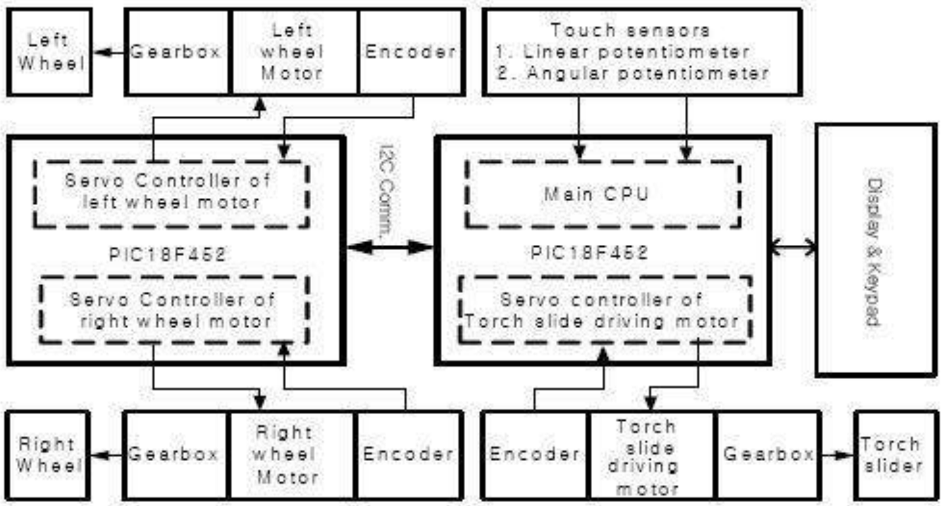


Figure 11. Control System Configuration adopted from Dung et al. [63].

Incompetent seam tracking is proved to be crucial for quality problems in welding process. Xu et al. [65] established a new technology for seam tracking with self-designed passive vision sensor that is capable of producing clear welding image for seam tracking. Then, a segmented self-adaptive PID controller will monitor seam tracking in order to surpass seam forming quality requirements. Without doubt, intelligence control system is currently the best applied method practically. There are a lot of works done by researchers to create the modernized system. For example, Liu et al. [66] created an intelligent motion navigation method that capable of estimating zero accident path, thus minimize the energy utilization. It gives significant impact in reducing power supply utilization. The programming also provides welding process of high quality and efficiency. Chu and Tung [67] produced an automatic control system which equipped with fuzzy gain scheduling controller that is capable of performing human tasks and shielded metal arc welding. Zhu et al. [68] explained in their paper how the starting position of weld seam is detected using pattern match technology. Faster matching technology avoid time consuming process and the ability of the system give good technical support to the welding robot.

In welding process, sensor is used for estimating the condition of work piece, followed by transforming the information to the robotics system for further action. Normally sensor is in form of portable micro-electronic device and play important role in the whole mechanized system. Park et al. [69] explained about mobile welding robot used for application in U-type cells. System is equipped with touch sensor to modify the misplaced in positioning and dimensioning. Nevertheless, the price of the robot is very high and it is also very heavy. Sweet [70] has developed an application of vision sensor system using general electric P50 as shown in Figure 12. Welding robot produces excellent results for welding joints with 12mm at 12cm/s welding speed. Kim et al. [71] established a system to calculate the position and orientation of end effectors. It adjusts 19 controllers' gains for 6-axis manipulator. The maximum magnitude frequency goes down by 54%. Luo and Chen [72] developed a seam tracking controller that equipped with laser-based camera. The system has the capability to calculate the starting welding position and to employ two-point linear interpolation in order to detect missing seam points.

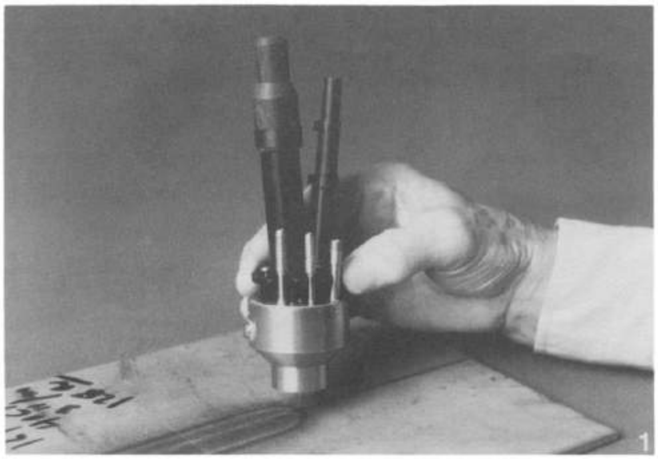


Figure 12. Integrated Torch Sensor

Design and modeling, control system and sensing ability in robotics arc welding focus on vital factors for innovation. Heat transfer, arc characteristics, and weld bead geometry are the important factors that influence the concept in designing welding robot. These factors will directly affect the total cost and power supplies of the whole production. For control system, manufacturers will concentrate more on weld penetration ability, control of joint profile and also control of filling rate. Example presented in this paper is fuzzy logic control, neural network control and knowledge-based control. Seam tracking accuracy is also critical in ensuring high quality product. The same goes to sensor ability. It will depend on how fast a sensor can transform the information from the work piece, variety of application of the sensor and also covered area of the sensor.

3.3Friction stir welding (FSW)

In the relatively short time since its invention, the new welding process has found potential applications in a number of industries including aerospace (military/civilian aircraft, aircraft parts, fuel tanks, rockets), land transportation (tailored blanks, truck bodies, armor plate vehicles, wheel rims, engine and chassis cradles, fuel tankers, motorcycle and bicycle frames), railway (tankers and wagons, container bodies, underground carriages and trams), shipbuilding and marine (panels for decks, sides, bulkheads and floors, helicopter landing pads, offshore accommodation, hulls and superstructures, aluminum extrusions), construction (aluminum bridges, window frames, aluminum pipelines, heat exchangers, facade panels), electrical (bus bars, electrical connectors, electric motor housings, encapsulation of electronics), and gas (tanks and cylinders) [73].

Unlike fusion welding processes, for example arc welding, electron beam welding, and laser welding, the FSW process takes place in the solid phase below the melting point of the materials being joined (Figure 13). Advantages that have been cited for the process include the ability to weld alloys that are difficult to weld by fusion welding processes, excellent mechanical properties, low distortion and shrinkage, no fume, porosity or spatter (frequently associated with arc welding), energy efficient, and ability to be used in all positions [73]. Additionally, FSW uses a non-consumable tool, requires no filler wire, or gas shielding, and is tolerant of thin oxide layers.

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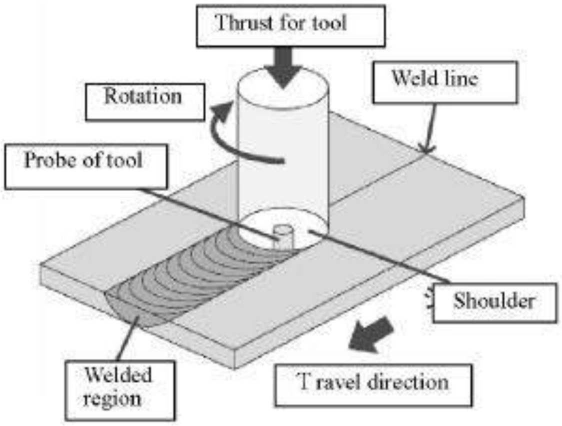

Figure 13. Principle of Friction Stir Welding

FSW applications can be expected to expand substantially when industrial robots are used more in place of currently employed heavy-duty machine tool equipment. This will permit welding three-dimensional contours, with the robots offering the advantages of greater flexibility and availability, and relatively low cost [73]. It was not until the Friction Stir Welding Symposium in Gothenburg, Sweden in 2000 that the first robotic FSW application was demonstrated [74]. Two research groups were presented successful welding in aluminum where one group was using a serial kinematics robot [75] and the other using a parallel kinematics robot [76]. The work by C. Smith was initiated in 1997 with internal feasibility studies at Tower Auto-motive [77] and could be seen as the first investigation of robotic FSW.

The most common for industrial robots is serial kinematics design. It is widely adopted in the automotive industry and has been tested in the area of FSW by several research groups in the past [78-80]. However, alternative systems have also been demonstrated using parallel kinematic robot [76]. Such robot systems have a much better stiffness but lack the large workspace that serial kinematics robots offer and are far more expensive. A serial kinematics robot has great advantages but has the limited stiffness [75]. A robot also consists of many components with certain flexibility. Inaccuracies in robotics are mainly caused in the joint by torsional flexibility in the gears, bearing deformation and shaft windup [81].

Since 1996, efforts have been put into creating a robot based FSW technology [82]. Early in the development of friction stir welding, it was recognized that FSW had many advantages over other joining processes for aluminum in numerous applications. However, it was often concluded that FSW was uncompetitive in many of these applications for a couple reasons. First, the high forces that FSW requires caused the need for expensive custom-built machinery [83]. These custom built machines also created relatively high productivity losses in many applications, due to the inability to achieve high duty cycles (‘on time’). These two factors made FSW uncompetitive, especially where robotics is currently employed. To overcome this issue, the robotic FSW solutions were developed [83].

Neos Tricept type robots have a parallel kinematic structure, which yields a significantly stiffer structure than the serial structures typically used with other industrial robots (Figure 14). This parallel kinematic structure has definite advantages when attempting to develop robotic FSW systems. However, these type of robots have rather limited working envelopes when compared toserial kinematic structures. Additionally their cost has been significantly higher than standard serial kinematic robots [83].

Figure 14. Neos Tricept Robot

Since the welding procedures do not call for widely varying operating parameters, stable robust force feedback control can be readily implemented with properly sized industrial robots [73]. For example, Smith [78] have reported a robotic FSW system based on the use of an ABB IRB 7600 articulated robot arm, as shown in Figure 15. This robot has a 500 kg payload. The spindle and motor drive for rotating the pin tool are attached to the end plate of the manipulator. The spindle is designed to accept the forces (both axial and radial) required for FSW and it additionally contains force sensing for force feedback control. Smith [78] have shown that the system is capable of maintaining constant axial force even under conditions of a programmed 3mm change in component surface height over the length of the weld.Furthermore, these robots are stiffer than the previous serial kinematic robots. Another important advancement with these new robots is the modern, more powerful control systems that allow for significant improvements in the force control system capability [83].

Figure 15. ABB IRB 7600

An ABB IRB 940 (Figure 16) is a tricept type robot. Its parallel design provides an extremely stiff structure that is capable of a vertical force of 1,300 kg [84]. The high stiffness of this arm design is derived from the use of three parallel linear actuators connected to a center tube in the middle with three additional axes on the wrist [73]. The working envelope of this type robot is less than the articulated serial arm and it provides excellent rigidity for stable force feedback control. Strombeck [85] have reported the use of a parallel robot for robotic FSW with force feedback control and it reported an excellent result with the system.

This type of robot is much more competitive with the serial kinematic structures. In applications where a relatively small work envelope is required or where more force capability is required, the use of this type of robot will be competitive with other robotic joining technologies. This type of robot would also be helpful in applications where machining of the part is also required. A further benefit of this new solution is that this robot now has a common architecture with the serial kinematic robot, making integration of other FSW hardware and software relatively seamless [83].

Figure 16. ABB IRB 940

ABB IRB 6400 robot (Figure 17) has the open architecture that is required for any robotic FSW system. This robot system has been used to make thousands of parts, but its applicability in production applications is still questionable for several reasons [83]. First, the high duty cycles seen in production applications tend to overheat the robot’s motors. Secondly, the response time of the force control is still slower than would be required for production application. Lastly, the relative lack of stiffness of the robot can make development of weld paths challenging and require a highly skilled robot programmer. Thus, this robot system is relegated to prototype applications [86].

A FSW-robot cell was established at the Production Technology Centre in Trollhättan, Sweden. The project aimed to bring robotic FSW closer to industrial applications by eliminating constraints, related to the robotic implementation of the FSW process and by further control and automation of the process [84].


Figure 17. ABB IRB 6400 robot

The control system is adapted to a 5-axis controller and a force sensor for direct force control is implemented. The robot comes with several instructions for programming FSW of simple geometries. This robot system also comes with several software features for programming simple geometries such as squares, lines and circles. These functions only require some teach-points to define that geometry and the welding path with desired tilt-angle is calculated from those points. However, the robot did not include a function that can use offline-programmed robot paths for FSW.

Industrial robots would be a preferred solution for performing FSW for a number of reasons, including their widespread use in the automotive industry [87], their ability to repeatedly follow three-dimensional paths and their low costs. The use of an industrial robot for FSW could also be a major improvement because many process changes can be intercepted by a software adaption. The first industrial robots had insufficient stiffness and since they could not deliver the required down force, they were not suitable to use for FSW. However, nowadays there are robots with very high payloads of one thousand kilograms and more which are also very stiff. This makes a breakthrough of robotic FSW possible (Figure 18).


Figure 18. FSW robot welding automotive body parts at the Production Technology Centre

As mentioned previously, there are two different robot concepts useful for FSW which is parallel and a serial construction. A parallel construction is much stiffer and provides very good results but it has a few important drawbacks. The system is more complex, has a very limited workspace and the cost, compared to a serial robot with the same payload which is much higher. Nevertheless the compliance problems are very detrimental in a serial design robot where the design is more suitable for applications in the industry. The motor that use in the FSW robots can be either hydraulic or electric. According to Smith, the major advantage of hydraulic motor is it has a lower volume to power ratio, make it as the best motor choice in the industry.

4- Current Research Topics in Robotic Welding

4.1Path/motion planning

Once the programmer has defined all of the seams within the vehicle that are to be welded they then move onto the next programming task, which relates to planning the motions required for the robotic cell to correctly carry out the welds. In welding rapid manufacturing technology, path planning is equally important.

The problem of effective motion planning for industrial welding robots was discussed by Trnka and Bozek [88] in two parts. The first part dealt with current method for off-line motion planning. In the second part the presented work was done by one of the simulation systems with automatic trajectory generation and off-line programming capability. Some researchers considered a two-robot welding coordination of complex curve seam which means one robot grasp the work piece, the other hold the torch, the two robots work on the same work piece simultaneously [89]. They build the dual-robot coordinate system at the beginning, and three point calibration method of two robots' relative base coordinate system was presented. After that, the non-master/slave scheme was chosen for the motion planning, the non-master/slave scheme sets the poses versus time function of the point u on the work piece, and calculates the two robot end effecter trajectories through the constrained relationship matrix automatically.

Multi-pass weaving welding is usually used in thick plates [90]. Automatic path layout of multi-pass weaving welding is a key technology to realize robot automatic welding for thick plates. In a study by Zhang et al. [90], a user self-define path layout model was developed to realize teach offline programming for multi-pass weaving welding. Users can set the welding parameters of every pass, the number of layers and passes, and welding sequence according to the real welding technology. The developed system can produce the position, pose of welding torch and oscillation displacement of total passes automatically. The multi-pass welding shape is well and meets the actual production requirement through robot multi-pass weaving welding experiments for single V-groove thick plates. In order to solve the problem that the welding robot path planning in the production line of BIW is inefficient, some researchers analyzed the problem of the welding robot path planning and abstracts it into the TSP model [91]. Afterward, the optimal welding path was calculated using Ant Colony Optimization (ACO). The result shows that this algorithm is an accurate and effective tool for welding path planning.

A four freedom robot able to carry out automatic welding of offshore platform was introduced [92]. The kinematic design of the robot has been designed according to the welding seam feature of T/Y/K-joint. The path planning of T/Y and the obstacle avoidance technique are used to study the robot's collision avoidance welding on K-joint. In the process of K-joint path planning, the geometrical method was adopted to study the welding torch's posture in branch gap. For ensuring the postural stability of robot, the robot posture of a series welding points in single branch pipe condition was adjusted gradually in K-joint condition. For a mobile welding robot, its kinematic and inverse kinematic model was calculated based on the D-H method [93]. This method used the approach of interpolation to do path planning of a mobile welding robot with a 5-DOF arm, and adopt the method to make various welding path simulation. When the vehicle is walking across obstacles, it should do the welding at the same time.

Based on the UG/OPEN GRIP platform, a slicing and route planning algorithm was proposed [94]. The robot NC code can be created automatically after slicing the UG part model and executing the route planning algorithm. By using the RP technology together with welding technology, it slices directly the UG 3D entity model on the UG/OPEN GRIP platform. This method is more effective and can avoid the problem of low precision caused by the traditional slicing method which uses the triangles to approximate the 3D models.The proposed route planning algorithm generates a continuous route according to the feature of the model, improves the efficiency and quality of the modeling and largely reduces the stop and start operations of the welding torch.

A path planning optimization method was proposed by Wang and Chi [95] to add learning ability to teaching and playback welding robot. The optimization was divided into the welding points sequence improvement and trajectory improvement, which was done both on-line and off-line. Points sequence optimization was modeled as TSP and was continuously improved by genetic algorithm based strategy, while the trajectory between two welding points was on-line improved by an try-and-error strategy where the robot try different trajectory from time to time so as to search a better plan. Simulation results verified that this control strategy reduced the time and energy cost as compared with the man-made fix-order sequence. In the study by Liu et al. [96] the quantic polynomial interpolation was adopted between each two adjacent desired via points, the continuous trajectory is formed in accordance with the time course. The simulation model was developed using Sim Mechnics, the movement parameters and path were obtained by simulating, the simulation results indicated that the motional parameters and path can be accurately and effectively obtained for robot analysis and design. An automated programming system for the combination of a laser beam deflection unit, a laser scanner and an industrial robot was presented [97].[According to analyzing the optimum path planning of the arc welding robot, a new gene insertion greedy genetic algorithm was presented by Sun and Yan [98] to optimize the global path planning of the arc welding robot. The algorithm can be used in the multi-joint arc welding robot and also be used in the robot off-line programming.For the optimum welding path planning problem of 6 degree of freedom (DOF) mini welding robot, a path planning method was proposed based on genetic algorithm (GA) [99]. The off-line programming system of MOTOMAN-UP20 arc welding robot based on OpenGL visual technology has big position error. In order to resolve the problem, a novel method of real-time error correction was proposed [100]. It reduced position error by optimal path planning, and then the signal of real-time error correction was inputted to control robot for correct the robot path, to decreased all kinds of errors.

In view of the current BIW welding robot path planning for the lack of theoretical basis, a solution was provided which abstract the problem of robot path planning into TSP mathematical model [101]. After researching the calculation method of the mathematical model, an optimization program based on ant colony algorithm was given via Matlab. The results show that this solution is effective and with a faster speed.

A new developed system that can automatically plan welding path of space weld for arc welding robot was proposed [103]. Using VB6.0 as the programming platform, the system can generate the position and posture file of welding torch directly and automatically from a three dimension solid model, and convert the file into the robot program. In the experimental welding of the combined use of UP-6 arc welding robot system and S-350 MAG welding system, the correctness of the system have been validated.

In BIW assembly and joint workstations, several robots are usually used to do spot welding job simultaneously. There are many devices and the robot′s workspace is cluttered, the path planning is onerous and hard to be optimized by experiential methods. On the basis of analyzing assembly and joint workstations, a workstation with commercial simulation software was modeled and PRM algorithm was applied to implement the path planning for robot automatically [104]. An automatic path planning method, including the torch pose planning, was proposed to improve the flexibility and automatic planning ability of arc welding robot [106]. The virtual object, which representing the real object to be welded, was reconstructed firstly by non-rational B-spline surface from geometric polygonal mesh model or measured point cloud. Based on the reconstructed non-rational surface model, the tangent vector and the tangent plane of each sampling point on the space welding seam was calculated, as well as the normal plane of each sampling point. Thus the position and pose of torch with respect to each sampling point of space seam can be determined by the calculated tangent vector, normal plane and concrete requirement of welding process. The final path planning of arc welding robot in joint space was obtained by its inverse kinematics. Experimental results demonstrated the accuracy and the feasibility of the proposed method.

The omnidirectional path planning in 3D space of the welding robot was presented [107]. In order to make the obtained trajectory pass through the scheduled position, the spatial pose must be accurately calculated and the angle of every joint is interpolated using the cubic B -Splines. Thus, the accuracy of controlling error is high and the path planning program can be easily compiled.

A planning algorithm for multi-path/multi-layer circular locus was proposed [108]. The algorithm was applied to weld the nipples on the header of boiler. Multi-path/multi-layer circular locus was planned according to three teaching points, which was lapped head-on-end to satisfy the requirement of technology. For the nipples wherever they are arranged radially or axially, even if there are errors caused by positioning and thermal deformations, providing that nipple's position and orientation relative to the teaching one can be measured, the multi-path/multi-layer circular locus can be planned without teaching any more. This algorithm has been applied in welding robot for manufacturing power station boiler.

4.2 Image processing

With the development of the computer vision technology and image processing methods, numerous welding robots and some automatic welding machines are equipped with corresponding vision sensors to achieve different welding tasks in severe conditions. A weld pool image processing algorithm based passive-light-vision has been studied [109]. Firstly, they have designed a kind of method to directly capture the welding pool images of Gas Metal Arc Welding (GMAW) by a CCD camera with a narrowband filter. Next, using the median filter and wavelet transform eliminates noise and keeps the details of the image effectively. Then, they have proposed to adopt the threshold image segmentation for detecting the welding pool in the image. The segmentation between the connected components and the noises to include the welding pool with the spots and the block, have been realized by the method to mark the connected pixels. Finally, through the operations of pixel-by-column scanning and pixel-by-line scanning, the groove centerline and the welding torch centerline can be found out correctly and the deviations of the seam are also obtained. A structured light image processing technology was proposed by Yue et al. [110] for a pipeline welding automation projects and a vision-based pipeline girth-welding robot. I this process, the welding torch can accurately track the weld and complete the Omni-orientation welding automatically.

Some methods have been proposed to improve the robustness and adaptability of arc welding robots [111]. Image processing algorithm for feature extraction from structured light images of weld seam was discussed in the case of a large amount of strong reflection, arc light and splash disturbance. The processes consist of defining target region, selecting adaptive threshold and extracting feature points. Then a novel hybrid visual servo control method for arc welding robot was provided, in which the position-based and image-based visual servo method were integrated to increase the robustness of weld seam tracking.

The technology of capturing and processing weld images in real-time was analyzed in the study by Xu et al. [114], which is very important to the seam tracking and the weld quality control during the robotic gas tungsten arc welding (GTAW) process. An efficient algorithm of weld seam detection for butt joint welding from a single image was proposed [115]. A robotic vision sensing system for taking and processing the image of MIG welding pool of aluminum alloy was established [116]. A series of clear welding pool images were obtained during welding process. The welding pool's image processing and edge detection method was designed, which affects good conditions for MIG welding.

4.3Artificial intelligence

With the rapid development of modern automation and artificial intelligence technologies, their application in welding has become a hot research topic. Recently, there has been a rapid development in computer technology, which has in turn led to develop the fully robotic welding system using artificial intelligence technology. However, the robotic welding system has not been achieved due to difficulties of the mathematical model and sensor technologies. The possibilities of the fuzzy regression method to predict the bead geometry, such as bead width, bead height, bead penetration and bead area in the robotic GMA (gas metal arc) welding process was presented [120]. A well-known method to deal with the problems with a high degree of fuzziness was used to build the relationship between four process variables and the four quality characteristics, respectively. Using these models, the proper prediction of the process variables for obtaining the optimal bead geometry can be determined.

The possibilities of the fuzzy regression method in modeling the bead width in the robotic arc-welding process were presented by Xue et al. [121]. Fuzzy regression is a well-known method to deal with the problems with a high degree of fuzziness so that the approach is employed to build the relationship between four process variables and the quality characteristic, such as bead width. It is important to control the penetration depth of the weld pool during welding, so as to obtain a good-quality weld, but it may be difficult to detect the penetration depth directly by using a visual sensor. In order to detect the penetration depth, a penetration depth model was proposed by Hirai et al. [122] based on a neural network. During welding, a fuzzy controller adjusts the welding current so as to obtain the desired penetration depth. Since the performance of the fuzzy controller depends on fuzzy variables, its tuning can be performed by using the neural network model. The validity of the fuzzy neural network is verified by some welding experiments.

A Kinematics model of welding robot was built by Wu et al. [123]. An improved fuzzy controller (Fuzzy-P) for welding robot mobile platform was designed based on analyzing seam tracking control system. A novel robust control of welding robots for weld seam tracking in the task-space (TS) was presented in the study by Fateh [124]. The proposed control law includes a robust Takagi–Sugeno fuzzy controller, and two model-based control transformations named as feedback linearization and inverse kinematics. As the performance of control transformations is degraded due to the uncertainty, the fuzzy controller was used to compensate the effects of imperfect transformations.

Further, a fuzzy coordinator was introduced as a novel application of fuzzy controller by Fateh [125]. A control transformation from the task space to the joint space is required to control a robot manipulator in the task space. Because the actuators operate in the joint space while the manipulator is controlled in the task space. A conflict between two spaces is produced due to using an imprecise transformation. Fuzzy coordinator coordinates two spaces by modifying the control transformation affected by uncertainties. The fuzzy coordinator is designed simply and operates as a robust controller. The role of fuzzy coordinator was analyzed and illustrated in the robust control of a welding robot in the task space. A circular trajectory was planned for a welding task performed by a SCARA robot. The fuzzy coordinator was then used to improve the performance of control system affected by imprecise transformations including the imprecise path transformation and the approximated feedback linearization.

To solve the seam tracking problem of the welding mobile robot, adaptive fuzzy controller and fuzzy-Gaussian neural network (FGNN) controller were designed to complete coordinately controlling of cross-slider and wheels [126]. The fuzzy-neural control algorithm was described by applying a Gaussian function as an activation function, taking lateral slider position and the error between the robot moving direction and the seam direction as the inputs signals, and the adjusted angle for welding torch as the output, a specialized learning architecture was used so that membership function would be tuned in real time by applying the FGNN controller.

In the work of Zhang et al. [127] the Kinematic modeling of the developed welding mobile robot was presented and a real time seam tracking algorithm based on fuzzy neural network was proposed. At first, the kinematics behavior of mobile robot body and cross sliders action to the welding torch was investigated by the Denavit-Hartenberg Homogeneous transformation method and a full kinematics model was established. Then, a seam tracking controller based on fuzzy-Gaussian neural network(FGNN) was described by applying a Gaussian function as an activation function, taking lateral slider position and heading angle of the robot as input signals, and the adjusted angle for welding torch as output. For the curved weld seam tracking problem of wheeled welding mobile robot used in shipbuilding and large spherical tank welding, predictive fuzzy control method was proposed [128]. To overcome the disadvantage of rotational arc sensor which cannot detect the next seam position, the algorithm employed weighted least square fitting method to predict the weld seam next position and used linearization model to predict the robot next orientation and position. In addition, fuzzy control was adopted to deal with nonlinear characteristic of the system. The main advantages of this predictive fuzzy controller include small tracking error, small robot orientation delay angle, and the availability of a linearized predictive model that reduce the computing complexity, and the highly tracking quality. A convenient and effective close loop control scheme had been proposed to satisfy the aim of seam tracking based on the analysis of the welding-robot modeling and its control link [129]. With the introduction of fuzzy controller and PID controller and with the adoption of the simulation on the differentiated modeling, the characteristics of the hybrid manipulator were illuminated.

The transient values of welding voltage and current are measured in real-time under the condition of arc welding robot-based seam tracking on V groove of 10 mm-thick mild steel plates. Statistical processing for the transient values were carried out for two times, and the characteristic vector was set up for describing the welding electrical parameters under different levels of weaving amplitude and frequency [131]. Employing the fuzzy pattern recognition technique, the relationship between the characteristic vector and the weaving amplitude frequency was developed to provide the basis for analyzing quantitatively the effects of weaving amplitude frequency on weld penetration of V groove joints. According to the awful working condition for the special robot repairing hydraulic turbines and the characteristics of the welding process, such as disturbances, nonlinearity, strong coupling and so on, a kind of adaptive fuzzy control system for weld was designed on basis of adaptive theory and fuzzy control theory [132]. In Zhang et al.'s study [133], a genetic algorithm combined with graph theory was proposed for solving the problem of welding route planning in car body-in-white manufacture. By regarding the welding point and tool center point frame as spatial point to establish relationship graph, transforming constraint factors into directed relationship matrix and using minimum motion distance of welding gun as object function, a traveling salesperson problem model was established. Generation of legal initial population and processing of selection, cross and mutation genetic operators were based on directed relationship matrix. The trajectory of a revolute welding robot with six joints was planned in order to make the trajectory smooth and working time optimal [134]. The time intervals between each point to be welded in Cartesian space were coded in binary, and the trajectory was implemented using an adaptive genetic algorithm while considering constraints of displacement, velocity, acceleration and jerk of each joint. According to the optimal time intervals generated, the results of simulation on robot kinematics show that the method designed for robot trajectory planning can obtain the goal trajectory. This method can solve the premature convergence and slow convergence problems, comparing with the simple genetic algorithm.

The job scheduling methods of arc welding robot was proposed by Meng and Chen [135]. The job scheduling of arc welding robot was considered as a Traveling-salesman-Problem. Welding job scheduling was modeled and relevant job scheduling optimization methods are designed. Genetic algorithm and ant colony algorithm were applied to robot welding job scheduling first. Then, based on the characteristics of both algorithms, hybrid genetic ant colony algorithm was designed to improve optimization performance.

For the optimum welding path planning problem of 6 degree of freedom(DOF) mini welding robot, a path planning method was proposed based on genetic algorithm(GA) [99]. First, the kinematical equation of the wielding robot with a method D-H was found, and then an optimized welding path planning with the fitness function of energy consumption was given. Finally by means of simulated result on the 6 DOF welding robot, the correctness and feasibility of this algorithm was testified.

According to analyzing the optimum path planning of the arc welding robot, a new gene insertion greedy genetic algorithm was proposed to optimize the global path planning of the arc welding robot [98].This algorithm can be used in the multi-joint arc welding robot and also be used in the robot off-line programming.

Based on the greed genetic algorithm (GGA), utilizing the operation of gene transplantation improves the performance of the traditional genetic algorithm. The new algorithm is called the greed genetic algorithm with gene transplantation (GGAGT).This algorithm was applied to find the global sequence plan when the industrial multi-joint manipulator is used in the welding [136]. It is proved that the convergence of the result is improved and the range of the research is broadened while the scale of the group is not increasing and neither is the computation and at the same time the algorithm quickens up the speed of convergence and makes the possibility of leading to local convergence decrease.

For the error analysis of a welding robot, based on the Vittorio granularity encoding, an enhanced genetic neural network using binary and real-valued blend encoding method was presented [139]. The neural network topology adopts binary encoding which reserves the virtues of Vittorio granularity encoding, and the connection weights adopt real-valued encoding, the Solis & Wets algorithm brings the virtues of evolutionary programming and evolutionary strategy to the new genetic algorithm.

The problem of coordinating multiple motion devices for welding was considered in Wu et al.'s study [140]. This problem is complex as there are nine axes involved and a number of permutations are possible which achieve the same movements of the weld torch. The system is redundant and the robot has singular configurations. As a result, manual programming of the robot system is rather difficult to complete. This proposed approach to the coordination problem is based on a subdivision of tasks. The welding table was coordinated to align the weld point surface to be anti-parallel to the gravity direction. The six-axis robot was constrained to move the weld torch along the weld trajectory. Robot coordination was achieved by placing the positioning table in a good maneuverability position, i.e. far from its singular configurations and far from the motion limits of the six-axis arm and the motion limits of the track. While considering multiple criteria, including the welding orientation, a Genetic Algorithm was employed to globally optimize six relevant redundant degrees of the multiple robotic system for welding. The joint angles of the arm were generated by inverse kinematics.

A model was proposed for using the artificial neural networks when determining the relations of dependency between the observable parameters and the controllable ones in the case of robotic TIG Welding. The proposed model was based on the direct observation of welded joints, emphasizing on the process variables which have been arranged in the nodes of a neural network. The design of the network intended to achieve an architecture that contains four nodes in the input layer (all of them being controllable parameters) and two nodes in the output layer (one for each observable parameter).

An attempt has been made to develop a neural network model to predict the weld bead width as a function of key process parameters in robotic GMA welding [142]. The neural network model was developed using two different training algorithms; the error back-propagation algorithm and the Levenberg–Marquardt approximation algorithm. An intelligent algorithm was proposed to understand relationships between process parameters and bead height, and to predict process parameters on bead height through a neural network and multiple regression methods for robotic multi-pass welding process. Using a series of robotic arc welding, additional multi-pass butt welds were carried out in order to verify the performance of the neural network estimator and multiple regression methods as well as to select the most suitable model.

In order to detect the penetration depth, a penetration depth model was developed based on a neural network. During welding, a fuzzy controller adjusts the welding current so as to obtain the desired penetration depth. Since the performance of the fuzzy controller depends on fuzzy variables, its tuning can be performed by using the neural network model. The validity of the fuzzy neural network was verified by some welding experiments.

5. Conclusions

In order to fulfill modern day diversified requirements, significant improvements are needed for each element of welding robots. Robots must be able to integrate with their environment in order to produce optimum performance. The ability to present knowledge by using prior information and newly acquired information is another important element. This would provide people the combination of ideas they have explored. Most of the robots are designed to operate with human capability. Otherwise, it will reduce opportunities to be the main player in the market. People should provide robot with fully autonomous system rather than using panel to control them. Level of cooperation among robots is also important especially when solving complicated tasks. Working as a team, each part of the robot should communicate well and perform given tasks using best possible solutions. Power supply is another issue that should be included in the discussion. Since the world is turning into sustainable way of living, the developed system must be aligned with them. Instead of using electricity, manufacturers could use renewable energy or a closed-loop system which maintain the energy sources. All of the mentioned elements will contribute to a major change in technology of welding robot.

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