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Simulation of Spot Welding Robot for Automotive Manufacturing Application

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Abstract--- *One of the most important applications of industrial robots is spot welding which is used in high production applications mostly in automotive industries where mass production is required. The speed, precision, efficiency and the resulting cost reduction due to mass production are well accepted and well documented advantages of automation of spot welding process using robots. In order to meet the new challenges of increased global competition, manufacturers are forced to seek new technologies for improved production and cost reduction. Such cost cutting efforts can only be achieved by improving the offline programming method. Offline programming is one of the most crucial parts of modern automotive manufacturing process. The whole process design of the robotic spot welding is not simple and includes CAD design of the part, shape and complexity of the parts which needs to be spot weld, design of the robot work cell, design and selection of spot weld gun, required production rate, offline programming tool, robot calibration, work cell calibration, work piece positioner design etc. In this report an approach to implement the offline programming of robot based on simulation software with the process knowledge of car-body in white was proposed and partially developed. Some common problems such as motion simulation, collision detection and calibration can be partly solved by this approach. The results from offline programming (robotic simulation) show that the new welding layout is capable of achieving the manufacturer's target. The implementation of RSWS for automotive application is reasonable because of efficiency, accuracy and cost effective.*

Keywords--- *Robotic Spot Welding, Robot Simulation, Manufacturing Automation.*

I. Chapter 1

Introduction

Traditional manufacturing systems (often based on fixed automation) are being replaced by flexible and adjustable manufacturing systems. Due to its flexibility, programmability and efficiency, industrial robots are seen as a key element of modern flexible manufacturing systems. Nevertheless, there are still some problems that hinder the utilization of robots in industry, especially in the small and medium-sized enterprises (SMEs) . Programming an industrial robot by the typical teaching method, through the use of the robot teach pendant, is still a tedious and time-consuming task that requires some technical expertise. In fact, manual teach methods are often time consuming and imprecise. Nonetheless, the biggest problem that SMEs are facing is the lack of skilled workers, especially experts in robot programming and at the same time in specific manufacturing processes, such as welding and

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painting. Therefore, new and more intuitive ways for people to interact with robots are required to make robot programming easier. The goal is to develop methodologies that help users to program a robot with a high-level of abstraction from the robot specific language. Another important factor is the ability to program a robot off-line, without stop robot production. Many different solutions have been proposed in literature to create intuitive HRIs; through the development and implementation of user-friendly software interfaces dedicated to a specific industrial process ; using sensors attached to the human body to capture arm movements and thus teach the robot by performing gestures ; using vision-based interfaces ; and speech . Since over the past few years, computer-aided design (CAD) packages are becoming more powerful and accessible, CAD-based solutions related to the HRI problem have been common (see section II). Notwithstanding the above, due to the specific characteristics of an industrial environment it remains difficult to apply such systems in industry (many systems have not yet reached industrial usage). Thereby, the teach pendant continues to be the common robot input device that gives access to all functionalities provided by the robot (jogging the manipulator, producing and editing programs, etc.). In the last few years, the robot manufacturers have made great efforts to make user-friendly teach pendants, implementing ergonomic design concepts, more intuitive user interfaces, colour touch screens with graphical interfaces, a 3D joystick, a 6D mouse and developing a wireless teach pendant. Nevertheless, it is still difficult for an untrained worker to operate with a robot teach pendant. The teach pendants are not intuitive to use and require a lot of user experience, besides being big and heavy . In this paper is presented a CAD-based system to program a robot from a 3D CAD model, allowing users with basic CAD skills to generate robot programs off-line. In addition, the 3D CAD package (Autodesk Inventor) that interfaces with the user is a well known CAD package, widespread in the market at a relative low-cost. This system works as a real HRI where, through the CAD, the user operates in the real robot. The methods used to extract information from the CAD (position and orientation of rigid bodies in space) and techniques to treat/convert it into robot commands will be presented in detail. Several experiments were conducted to evaluate the system performance. The results showed that the proposed system is easy to use and within minutes an untrained user (without programming skills) can set up the system and generate a robot program for a specific task. The time spent in the robot programming task (using the system here proposed) is compared with the time taken to perform the same task but using the robot teach pendant as interface. Experiments were performed with a six-axis industrial robot in laboratory environment, giving to the reader a good insight into the problem. Finally, results are discussed and some considerations about future work directions are made.

Motivation Of this project

In this current work the project is focused on one of the sub-assembly processes involved in the spot welding process of automotive industry. This sub-assembly process is offline programming (OLP) of spot welding robots. This project tries to promote the integration of CAD Software, 3D Robotic Simulation Software and Robotic Spot Welding task in automotive industry so that different CAD software, 3D Robotic Simulation Software and different Robots can exchange information with each other for designing the spot welding assembly line in automotive industry. The project can thus be stated as optimised the OLP method of spot welding process in automotive industry.

Objective of the Project

According to statistics about half of the industrial robots around the world are engaged with various forms of welding job. This has reduced the high risk of radiation and hazard environment due to manual welding by skilled welders and increased the working condition and welding quality and efficiency. Robot technology is a high-tech integrated multidisciplinary of computer, cybernetic, mechanism, information and sensor technology, artificial intelligence and bionics. There are two ways of programming industrial robots. One is *Online programming and another is *Offline programming (OLP). Online programming consists of Teach pendant, Playback or Manual programming. Offline programming consists of Textual programming, CAD programming, Macro programming or Acoustic programming. More than half of the total industrial robots applied in factories over the world are in automotive industries and among them more than half of the robot's are in spot welding operation. The objective of this project work was to find a faster and more versatile OLP method for the automotive industry. Today offline programming and simulation software are the decisive and crucial tools of production planning and process in automotive industry. Automotive manufacturers are facing fierce competition from their competitors and always on the search for better and more efficient solutions for the production process.

Industrial robots use proprietary software and control systems. In future more and more engineers are bridging up the barriers of process simulation and OLP by advance digital manufacturing solutions enabling multi vendor systems. Today's industrial robotic sys-tem in general can be termed open and closed. An open system refers to the robotic sys-tem which is flexible and easy to develop further solutions on its platform, as a closed system refers to the proprietary solutions where only limited tasks can be done and development of the system is not possible without the manufacturers consent. ROS (Robot Operating System) or RRS (Realistic Robot Simulation) are examples of the effort towards more flexible and open frameworks. However the area of this project work is focused on automotive spot welding application of industrial robots. Long before a car is being manufactured the assemblies are de-signed in CAD software and a virtual copy of the robot and its environment in created in the simulation software where the robots programs are made, edited, simulated and verified before they are transferred to the physical robot. Robotic work cell simulation is a modeling based problem solving approach and the methodology consists of 6 steps, as shown below.

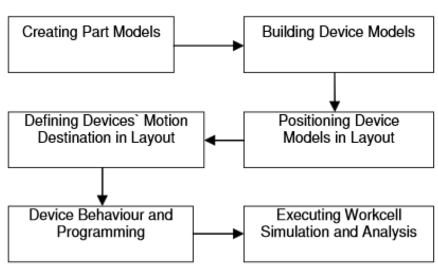

Figure 1-1 A methodology for robotic work cell modeling

For the project work CAD based OLP method was selected as the target is to propose a better method for the Virtual Manufacturing Process in the robotic spot welding application. The project work was done on the Factory Simulation and OLP software from Visual Components. The benefits of CAD based methods are verification of the following facts –

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- Components attitude in space.
- Movement of components and tools.
- Are working points reachable?
- Time needed for movement.
- Collision with environment.
- Checking for alternatives.
- OLP with generation of robot program

II. CHAPTER2

INDUSTRIAL ROBOTICS

In this chapter the most important features of current industrial manipulators are going to be discussed. In modern flexible manufacturing systems robots are essential elements. Traditional manufacturing systems are now vastly replaced by flexible manufacturing systems (FMS). The behavior of an assembly system is never completely predictable and can be hardly anticipated, because it has many sources of uncertainty . Those are –

- Material and parts variation
- Fixturing errors
- Positioning errors
- Auxiliary manufacturing process equipment error

Flexible manufacturing is the current approach to minimize production costs. In a modern flexible manufacturing system industrial robots are seen as the key element because of their high efficiency in flexibility and programmability . Automotive spot welding has always been one of the major applications of robots. In old days large, heavy car body parts have been held by clamping jigs, tacked together by operators using multiple welding guns and then spot welded manually. The industrial revolution changes the pace and competition of the automotive industry and it all started back in 1966 when first steps were taken to use a robot to guide the welding guns and combine the control of the robot with the control of the gun. In 1969 General Motors in USA installed 26 Unimate robots in a car body spot welding line. Then in 1970 Daimler/Benz in Europe used Unimate robots for body side spot welding. Currently there are big robot companies like ABB, Motoman, Kuka, Comau, Nachi, Fanuc etc. which provide the automotive industry with specialized robotic spot welding systems.

2.1. Types of Industrial Robots

Articulated – This robot design features rotary joints and can range from simple two joint structures to ten or more joints. The arm is connected to the base with a twisting joint and the links are connected via rotary joints. Cartesian – These are also called rectilinear or gantry robots. Cartesian robots have three linear joints that use the Cartesian coordinate system (X, Y & Z). They also may have an attached wrist to allow rotational movement.11

Cylindrical – The robot has at least one rotary joint at the base and at least one prismatic joint to connect the links. They work within a cylindrical work envelope.

Polar – The arm is connected to the base with a twisting joint and a combination of two rotary joints and one linear joint.

SCARA – Commonly used in assembly applications, this Selective Compliant Assembly Robot Arm for robotic assembly features two parallel joints.

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Delta – Jointed parallelogram connected to a common base. Delta robots are heavily used in food, pharmaceutical and electronic industry and capable for fast and delicate movements.

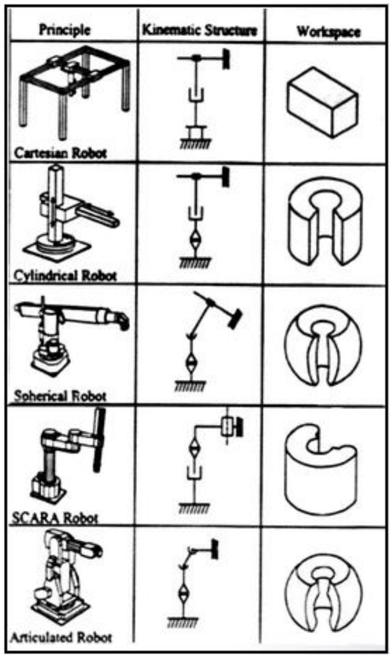

Figure 2-1 Types of Industrial Manipulator Arms

Programmable Industrial Robots

In today's industry programmable automation is the key focus and it is adaptable to manufacture a wide variety of products in variable lot sizes with mass production costs. Today's modern factories are designed with industrial robots, numerical control of ma-chine-tools, computer aided design and manufacturing and production information and control . The major applications of programmable robots are with sensors to material handling, inspection and assembly operations e.g. spot welding, arc welding, gluing etc.

Table 2-1 Comparison of different robotic arms

Robot	Joints	Coordinates	
		Advantages	Disadvantages
Cartesian	prismatic waist	*linear motion in three dimension	*requires a large volume to operate
	prismatic shoulder	*simple kinematic model	*workspace is smaller than robot volume
	prismatic elbow	*rigid structure	*unable to reach areas under objects
		*easy to visualize	*guiding surfaces of prismatic joints
		*can use inexpensive pneumatic	*must be covered to prevent
		*drives for pick and place operation	ingress of dust
Cylindrical	revolute waist	*simple kinematic model	*restricted work space
	prismatic shoulder	*easy to visualize	*prismatic guides difficult to
	prismatic elbow	*good access into cavities	seal from dust and liquids
		and machine openings	*back of robot can overlap work volume
		*powerful with hydraulic drive	
Spherical	revolute waist	*covers a large volume	*complex kinematic model
	revolute shoulder	from a central support	*difficult to visualize
	prismatic elbow	*can bend down to pick objects	
		up off the floor	
Articulated	revolute waist	*maximum flexibility	*complex kinematics
	revolute shoulder	*covers a large workspace relative	*difficult to visualize
	revolute elbow	to volume of robot	*control of linear motion is difficult
		*revolute joints are easy to seal	structure not very rigid at full reach
		*suits electric motors	
		*can reach over and under objects	

2.2. Industrial Robot Programming

Most of the applications of industrial robots are in the field of handling, welding and assembly. This section will discuss one of the most important topics regarding the efficiency of industrial robots i.e. motion planning. One of the most challenging topics of robot motion planning has been advanced path planning or trajectory planning, intelligent collision avoidance and there have been numerous researches to develop this kind of motion planning. A short introduction is given below on some of the current researches done on this topic.

2.2.1. Collision Free Trajectory Planning

There are algorithms for collision free path generation which are computed in complex space. In robotic spot welding application almost all the robots are 6-axis articulated, while 7-axis articulated robots are also getting ground, and spot welding paths are often complex and many obstacles on a sequence of spot welds. With traditional tools available in the OLP software the spot welding initial motion planning can be done quite easily and quickly. Major time is required for fine tuning the path movements and making them collision free. In a collision free path planning algorithm is introduced for four Cartesian robotic arms in a PCB manufacturing application. Although the problem in spot welding application is quite different it's worth studying the procedure. A test bed was made which included a flying probe system, a path planning algorithm was introduced which is based on previous well established algorithm's like NN Algorithm, genetic algorithm, nearest neighbour algorithm, band division algorithm etc. For the test a mechanical structure with PCB holder and four Cartesian robotic arms were installed. A probe was mounted at the end of each arm. A computer vision system with two different micro-CCD cameras for inspection and an industrial PC for controlling the Cartesian robots were installed. The below figure shows the proposed algorithm for the calculation of the trajectory that each probe must follow to travel to the next test point in the PCB avoiding collision with the PCB as well as with other Cartesian arm.

2.2.2. Advanced Robot Controllers

Industrial robot performance is specified in terms of functional operations and cycle time. For assembly robots it's the number of pick and place cycles per minute, welding robots are specified with weld pattern, weave speed as well as the fast repositioning speed. For painting robots the deposition/coverage rate and the spray pattern speed are important. The performance of a robot is determined by several factors (Table 2-3):

Table 2-2 Robot performance factors

Speed	Accuracy
Acceleration	Component Life
Repeatability	Duty Cycle
Resolution	Collision Detection

Major reasons for failure in electrically powered robots are actuators, transmissions and power/signal cable. Mean Time Beτtween Failures (MTBF) should be a minimum of 2000h online and ideally at least 5000 operating hours should pass between major com-ponents preventive maintenance replacements schedules .

Collision detection in industrial robotics has been developed from overload (slip) clutches, elastic members and padded surfaces to vision system and proximity sensors. In modern automotive plants where in a single station at least 4-6 robots work in syn-chronization is very common where sometimes the arms of robots works within centimetre proximity of each other. Advanced motion planning and collision prevention al-gorithm has made this possible.

Robot manufacturers have been constantly working to develop their robot's controller, to allow them for coordinated movement of several robots and simultaneous working on the same work piece. Robotics is widely used in the automotive industry for automated assembly, welding, painting fabrication, and production lines. Consequently, automo-tive manufacturers are constantl

2.3. History of Factory Simulation Tools

Today Simulation is the most multifaceted topics that an industrial, mechanical or automation engineer faces in the workplace. Today simulation software are extensively used to increase production capacity, increasing competitiveness and profits of the company.

First tools for factory simulation can be traced back in the 70's. These tools were developed to study discrete event simulation. These tools took numbers from timing studies from the production line, analyzed them and generated data which aided the industrial engineer to run experiments for manufacturing process improvement. Later 2D charts and graphs were included to the simulation tools. simulation tools with 3D models came to the markets on 80's. They were mainly based on robotics application and had physics functionality within. This software was able to simulate the motion of the robots and check for collisions. This was the revolutionary step of factory simulation from a 2D world to the 3D world.

In 90's the first intelligent simulation software came to the market which were able to represent 3D graphics capabilities and discrete event simulation capabilities together and this revolutionized the manufacturing industry. Later physics was included with the development of advance 3D engine platforms. Today the simulation of manufacturing processes like welding, machining, gluing, sorting, palletizing, assembly, packing, handling and many more are planned, designed and tested in the 3D world with the factory simulation software almost as precisely as the real world. The machines and robots programmed in the virtual world and then those programmes transferred and executed in the real world with least effort.

Two common fears of simulation in early 80's were:

1. Simulation is extremely complicated, so only experts can use it.
2. Simulation takes forever because of programming and debugging.

Today, CAD and simulation software are advanced to such a state that the software enables the user to model, execute and animate any manufacturing system in any level of detail. A complex 2000-foot conveyor, articulated robot, automotive BIW, machine tools, process station with several machines and robots, factory floor with discrete production system can me modelled in minutes to hours.

One of the major challenges of Automatic Path Planning has been researched in various approaches. One of them is a reconstructed surface model. In a virtual object was proposed which represents the real object to be welded, and is constructed from geometric polygonal mesh model or point cloud. From the surface model tangent vector and tangent plane of the sampling points are calculated. From this calculated tangent vector and normal plane the position and pose of torch of each sampling point is determined and the final path planning of arc welding robot in joint space is obtained by inverse kinematics.

2.4. Offline Programming (OLP)

OLP (Offline Programming) is the way to teach a robot its tasks without any connection to the robot or stopping its current task. It allows developing new design, faster and tasking creation, creating complicated tasks in a very easy way, improving cycle time without taking the real robot out of production .

The simulation software provides a virtual environment of the real robot work cell. In this virtual world the user can import external CAD files, model parts and fixtures. Then the user can create the tasks for welding, palletizing, material handling or painting with the robot. The reach ability and accessibility of the end effectors of the robot can be verified in different positions and the best one can be assigned. This same job with the real robot would be enormous time consuming task. Then the simulation is run and checked 20 for reach ability, collision detection or any other errors which can be then fixed. Motion path optimization and cycle time is analysed from the simulation. Finally using a translator the robot program is generated and downloaded directly to the robot controller . The following sections some reference to the research works done on advanced motion planning of industrial robots

2.5. Robot Calibration

There always exists a deviation between the offline program and real world execution of the OLP on a real robot. The reasons for the deviation can be classified into geometric parameters and non-geometric parameter . Geometric parameters are backlash, deflection due to unloaded robot weight and load applied to each joint. Non-geometric errors include transmission system errors between gears and thermal strain.

A typical welding line with 30 robots and 40 welding spots per robot takes about 300 hours of robot teaching. The most difficult part is to determine accurately a desired location in the workspace. Robot pose errors are attributed to several sources a) constant errors in parameters (link length and joint offset) b) position errors (compliance, gear transmission) and c) random errors (due to the finite resolution of joint encoders). Robot calibration can be done by model or modeless methods. Researchers have used specific kinematic models that depend on a particular robot geometry and calibration method. Model identifiability has already been addressed , and experimental and simulation results using a rational technique was shown by Motta and McMaster and Motta, Carvalho & McMaster to find an optimal model for a specific joint configuration, requiring a few number of measurement points (for a 6 DOF robot only 15 measurement points) for a model with only geometric parameters

2.5.1. Steps of OLP

The first step to OLP is to model the whole robot work cell in 3D. This is essential to test the a) robot movement b) reach ability c) collision detection and d) process related information for generating an error free offline program in the robot. With OLP the robot programs can be developed earlier in the design/production cycle without hampering the current production process. Moreover generation of OLP is a lot easier and efficient compared to jog and teach method. As simulation is incorporated with almost all OLP methods so a) robot movement b) robot collision c) productivity and d) safety are pre-checked minimizing the chance of error.

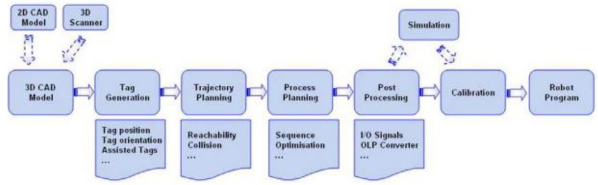

Figure 2-2 Key steps of OLP.

2.5.2. Generation of 3D CAD model

Usually 3D models are generated by using different CAD software. In case of changing dimensions there are several methods to generate the required 3D model. One of them is using a 3D scanner to capture the work piece geometry [29]. The 3D scanner generates a point cloud and it is converted to the surface model of the work piece. When only 2D CAD is available the 3D model of the work piece can be obtained in three ways a) mul-tiple view of 2D drawing b) additional sensors or c) simply programming the robot in 2D . There are different types of CAD files and current OLP software can import almost all well known CAD files to their own compatible format. There is soft-ware companies whose business is to develop common platform (CAD kernel) related to read/write different CAD file types e.g. Coretech (Germany), Hoops (USA) etc.

2.5.3. Tag Creation

OLP software has built-in functions to generate tags with a specific tool centre point (TCP) from features such as corners and edges, frames or small geometry features. In this thesis work the developed Add On [Spot Welding] tag points have been created from a *.csv file and geometry features in the CAD model. There are also assistant tag points 24 e.g. home points, approach points and retreat points. The position and orientation information of the TCP to reach each tag point is automatically created by the OLP software. Research is going on to automatically extract robot motion information from the CAD data

2.5.4. Trajectory planning

Inverse kinematics of industrial articulated robots usually has multiple solutions in the Cartesian space. Trajectory planning includes a) motion type- (linear/joint) b) joint con-figuration c) joint speed d) joint acceleration/deceleration e) reach ability and f) collision detection. In this thesis work the developed Add On [Spot Welding] the offline programmer can assign retract distance to each spot welding tag point, also assign approach and retract via points for the start and end of a spot weld sequence. Also the orientation of a group of spot welding tags can be rotated along X axis, Y axis or Z axis to any required degree for the best configuration.

2.5.5. Process planning

The requirements of a specific process needs to be studied carefully first. It is very essential in the sense that the success of automation of the process depends widely on careful study of the requirements of the process development. Process planning includes a) optimization of resource b) robot selection for the process c) calculate the number of robots needed d) productivity e) robot workcell design f) material handling process de-sign g) calculation of cycle time etc. For processes which involves large number of spot welds in limited cycle time can be treated as the “travelling salesman problem”(TSP) a solution which is based on a genetic algorithm.

2.5.6Simulation

In this step the simulation of the process is run in the simulation software. The robot runs and does its works as programmed by the offline programmer. This gives a very clear visualization of the process, what is going to be implemented in the real world. From the running simulation the offline programmer can see and calculate the flaws in the process, and correct them as necessary. He can calculate the process deadlocks, cycle time, productivity, resource utilization and get all these data in a graphical (graph/chart) format or numerical format (excel or *.csv). The greatest benefit of simulation is that all the process can be verified beforehand without the need of any physical robot or other machine's and removes the risk of any wrong/inefficient implementation of robot's or machines in the final stage.

2.5.7. Post Processing

The robot program in the simulation software is after satisfactory verification implemented to the real robot in the physical world. A conversion in the middle of OLP soft-ware and the real controller is utilized to convert the robot program in the OLP software to the program language of the specific robot target. Post processing of robot programs 25 Is a special issue for all the generic OLP software as the robot program needs to be made compatible for different robot manufacturers. It is still an issue that straight for-ward robot programs with just I/O signals and linear or point-to-point movement in the OLP software can be converted for the real robot specific language without much problem but it's tough to implement the intelligent programs (conditional loops, multitasking etc.) in the software to the robot specific program. For that the generic OLP soft-ware needs to have the virtual controller from the specific robot manufacturer. E.g. Visual components have the access to virtual controller of Kuka, Staubli and Motoman.

2.5.8. Calibration

Unfortunately in the real world the dimensions, position and orientation of the CAD models are not the same as in the virtual world or simulation world. So the work cell needs to be calibrated to make the robot program perform its task without collision or error (positioning error or mishandling etc.). Calibration is divided into two sections i.e. – Robot Calibration and Work cell Calibration; a) **Robot Calibration** is the process of determining the actual values of kinematic (position, orientation of links and joints) and dynamic parameters (joint mass, joint friction etc.) of an industrial robot (IR). An industrial robot needs to be calibrated after certain hours of operation. A calibrated robot has a higher absolute positioning accuracy than an un-calibrated one. b) **Work cell Calibration** means the calibration of its tools and the work pieces/fixtures in the work cell. It minimizes occurring inaccuracies and improves process security.

III. CHAPTER 3

ROBOTIC SPOT WELDING

The high demand of spot welding has forced the automobile manufacturers to keep looking for new technologies to make faster and more accurate spot welding. There have been constant upgrades on the spot welding robot's and spot welding guns. Ad-vancement in both AC and DC weld controllers, electric servo powered gun, modular design of spot weld guns, using lightweight aluminium metals in the weld guns are the forefront of the new spot welding technology. Another development is to use multiple robots with a single controller which enabled for multiple robots

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to work in a closely confined space without the risk of collision. Also especially for a dense robot popula-tion, in the robots there were modification of different castings and designing shorter arms but utilizing the same motor and sensors of the parent bigger version robot. Spe-cialized robots have been designed for spot welding application and they have utilities (air, water and power) routed in cable harnesses through the arm and out to the robot wrist, this greatly reduced downtime associated with external cables. Other improve-ment in automated spot welding was use of a pedestal or a stationary weld gun. The robot moves with the part to the stationary pedestal which holds the weld gun. A spot weld gun can weigh a couple of hundred kg while a panel can be 20-30 kg. In this ap-proach the robot dressing is minimized, part changeover is easy and capital equipment like robot is highly utilized all the time. To improve the weld cell uptime EOA systems an “Intelliflow Water Saver” was applied which monitors the temperature and coolant flow rate to the entire cell including weldgun, transformer, shunts, cable etc.

3.1. Spot Welding Process

Resistance spot welding is an efficient process to join vehicle body parts, by the means of strong interaction between electrical, thermal, metallurgical and mechanical phenom-ena . Spot welds are normally used to join vehicle parts upto 3 mm in thickness. There is a thickness ratio which should be also maintained, usually which should not be less than 3:1. Spot weld diameter ranges from 3mm upto 12.5 mm .

Principle

Spot welding is one form of resistance welding where two metal sheets are joined to-gether without using any filler material by applying pressure and heat to the area to be welded. The process uses copper alloy electrodes for applying pressure and electricity, the material between the electrodes yields, squeezed together, it forms ‘nugget’ of mol-ten materials which when solidifies forms the welded joint.

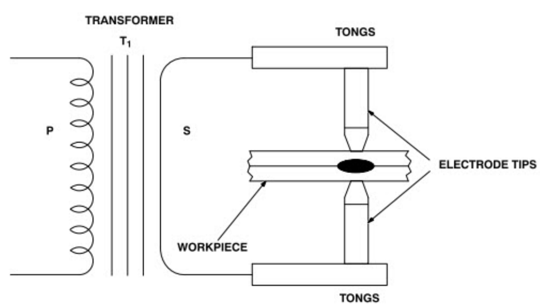

Figure 3-1 Principal of resistance spot welding.

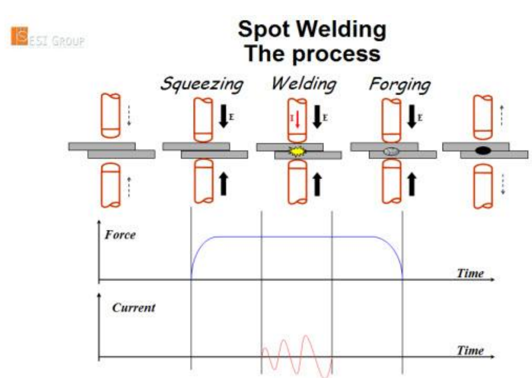

Figure 3-2 Force and Current analysis of spot welding process

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Heat Generation and Time Cycle

The heat generated while spot welding process is directly proportional to the resistance at any point in the circuit. Formula for calculating generated heat as following [45]: $H{=}I2RTK$

H = Heat
I2= Current Squad
R = Resistance
T = Time
K = Heat Loss

Control of time is an important factor as too long or too short time will lead to gas po-rosity, expulsion of molten metal or smaller weld nugget. Sometimes time is the only parameter that can be controlled in a spot welding operation when the current type is a single impulse [45]. The time cycle of resistance spot welding is shown below

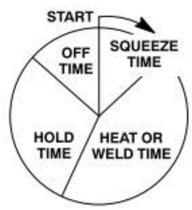

Figure 3-3 Heat genearation while spot welding

Spot Welding Parameter

Parameter setting is very important in spot welding process, which depends on the mate-rial of the sheets to be welded, sheet thickness, thickness ratio, electrode dia etc. As spot welding application in automotive industry is incredibly huge, the American Welding Society (AWS) has established a standard which is published in the book – "Specifica-tion for Automotive Resistance Spot Welding Electrodes" [46]. The table below gives a target value for welding parameters although one of the important parameters (metal type/material) is not mentioned.

Planning Robotic Spot Welding Lines

In order to plan a robotic assembly spot welding line which meets a the manufacturer's specific production needs the engineers have to design a detailed and optimized solu-tion. Design data from the product to be manufactured can be brought together to give an estimate of the machinery and equipment (robot, conveyor, fixture etc.). These in-clude the following :

♣ The parts to be assembled
♣ The geometrical conformation of these parts and the corresponding number of stations required.

Sheet thickness, t [mm]	Electrode force, F [kN]	Weld current, I [A]	Weld time [cycles]	Hold time [cycles]	Electrode diameter, d [mm]
0.63 + 0.63	2.00	8 500	6	1	6
0.71 + 0.71	2.12	8 750	7	1	6
0.80 + 0.80	2.24	9 000	8	2	6
0.90 + 0.90	2.36	9 250	9	2	6
1.00 + 1.00	2.50	9 500	10	2	6
1.12 + 1.12	2.80	9 750	11	2	6
1.25 + 1.25	3.15	10 000	13	3	6 7
1.40 + 1.40	3.55	10 300	14	3	6 7
1.50 + 1.50	3.65	10 450	15	3	6 7
1.60 + 1.60	4.00	10 600	16	3	6 7
1.80 + 1.80	4.50	10 900	18	3	6 7
2.00 + 2.00	5.00	11 200	3x7+2	4	7 8
2.24 + 2.24	5.30	11 500	3x8+2	4	7 8
2.50 + 2.50	5.60	11 800	3x9+3	5	8
2.80 + 2.80	6.00	12 200	4x8+2	6	8
3.00 + 3.00	6.15	12 350	4x9+2	6	8
3.15 + 3.15	6.30	12 500	4x9+2	6	8

Figure 3-4 Welding parameter [45]

♣ The distribution of spot welds and the number of robots required to weld them.
♣ The production rate and the number of lines required to meet the production needs.
♣ The desired degree of flexibility.
To complete the design additional information is still needed:
♣ The basic principles relating to the transfer and positioning of the assembly.
♣ The final selection of the robot, its equipment and its installation.
♣ The environment and the available space.

3.2. Simulation Planning

Advanced versions of today's industrial robotic simulation software already support following features:

- Uniquely structured environment lets the user to quickly enter the geometry and production requirements of a model.
- Expert system technology generates details automatically while windows and pop-up menus guide the user through the modelling process.
- Parts can be modelled completely parametric with functions and formulas. Changes can be made quickly and easily with far less chances of errors.
- Built in material handling templates make the user more productive and faster programming.
- The user can verify and test designs, explore more alternatives and catch system glitches and 3-D animation before implementation.
- 3-D graphics are automatically created as the user enters data.
- Results can be communicated in real time animation. Robots can be operated/ monitored from the 3D simulation with the help of virtual controller. OLP soft-ware have virtual controllers according to their partnership deals with the robot manufacturers.

All the simulation software in the market for process-planning and offline programming have various tools and algorithms for making process simulation of robotic spot weld-ing and arc welding. In this chapter the leading simulation software) are discussed.

3.3. Steps in OLP of Robotic Spot Welding

The focus of this thesis work is related to spot welding line in Automotive Industry. Spot welding is one of the most mature applications in robotics. The high demand for popular models of cars, to keep in pace with competitors in recent years big car makers have invested heavily in developing intensive automated spot welding techniques with short set-up time, modular & lightweight systems with increased cycle times and im-proved end of arm tooling(EOAT). Robotic welding plays the key roll enabling car companies to keep pace with demand for new, advance and higher quality product. Au-tomakers are always on the search for robots with greater repeatability and weld re-quirements down to ±2 mm.

In current practice the first step of OLP with spot welding is to model the car in com-panywide CAD system like AutoCAD, SolidWorks, Creo, CATIA etc. Then fixtures are designed which is going to present the parts to the welding robots. These fixtures are made by specialist and certified tooling companies. The points of fixture which are go-ing to clamp the car part are measured very precisely using a 3D co-ordinate measuring device. These measurements are recorded using manual theodolites and standard theod-olite triangulation. Recently also the photogrammetric method is used for measurement.

Usually spot weld guns are bought from the weld gun manufacturing companies from an array already designed products. But with special requirements often the car manu-facturers ask for customized spot weld guns. The first fixture is then installed in the production line, using this position data the position of the robots in a station are defined. The position of the second fixture is defined based on the first fixture position and so on, all the way down the production line.

Next step is the whole workcell building in the simulation software by mostly imported CAD files. The robots are imported from the ready robot library or received from ven-dor. The co-ordinate frames representing the position and orientation of spot welds, via points, weld schedules, motion type can be defined in the CAD software e.g. CATIA and then exported to the simulation software in *.csv file format or all the information within the CAD model itself. A COM AddOn was developed as part of this thesis work to export the spot weld information to a *.csv file.

The robot program is generated utilizing the spot weld information. The wrist joint lim-its of the robot often limit the orientations that are achievable and the simulation user must be creative to define the joint configuration, robot base location and robot tool.

Then the simulation is run to check collisions and the designer plans a collision free path, but he also has to be careful that it doesn't add excessively to the overall cycle time. There is a difference between the cycle time in the simulation software and the real robot. The robot companies consider motion algorithms in their robot controllers of such commercial value that they always refuse to release this to their simulation ven-dors. But fortunately every simulation software company is able to establish strong business relationship with some robot vendors and they can integrate the "Black Box" or the unreadable part of the robot controller software. This makes it possible to get ac-curate cycle time from the simulation software as well reliable information of the colli-sion and near miss information provided by the simulation.

Next step is the calibration of the workcell and robot as well. Robots are designed to be extremely repeatable but not all that accurate (repeatabilities of 0.1mm and accuracies of 10mm or worse are not unusual). Once the robot is calibrated then the mountplate is attached with a pointer to measure the position of the fixture datum point. This is called "3 point touch up" and is used for positioning the model of the fixture correctly relative to the robot model within the simulation world. This makes the offline programming truly meaningful. Finally the correct tool offset is determined in the robot in the simulation world. If the tool dimensions are unknown or changed due to collision or modification then a tool calibration is carried out.

After all the above procedures are carried out, the robot program in the simulation is really ready to be downloaded to the real world. Badly implementing or ignoring any of the above steps can result in bad consequence which can include damage of robot to the damage of workcell equipment as well as human injury.

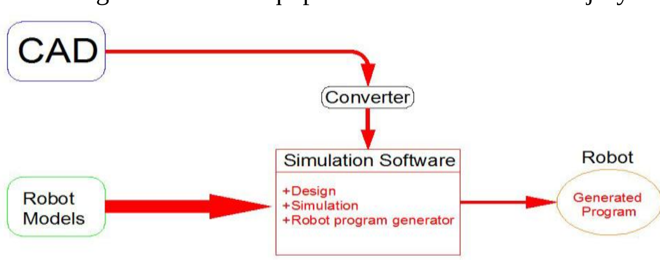

Figure 3-5 Steps in OLP of robotic spot welding

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IV. CHAPTER 4

4.1. Spot Weld Gun & Fixture Modeling

The algorithm for selecting a spot welding gun is presented in figure 4-6.

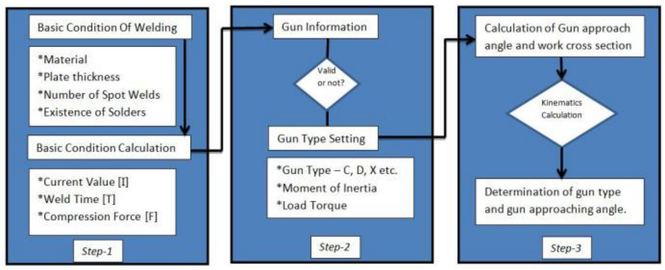

Figure 4-1 Algorithm for selecting the spot welding gun

In spot welding industry the job starts with designing the right gun and right jig for the parts which are going to be spot welded. The jig designer designs the jigs and the tool designer designs the robotic spot welding tools.

Spot welding guns are designed based on application. The guns can be categorized as following:

a) C-type (operating cylinder is connected directly to the moving electrode)
b) X-type (most common type)
c) D-type (mostly used for vertical welds)
Also every gun can be categorized in two sections -
a) Fixed jaw
b) Moving jaw
There is a fixed jaw in most of the spot weld guns. While offline programming at the tip of the fixed jaw, a frame is defined and this is the tool TCP for that spot weld gun.

Figure 4-2 C type spot weld gun

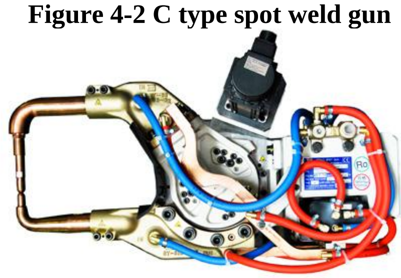

Figure 4-3 X type spot weld gun

Figure 4-4 D type spot weld gun

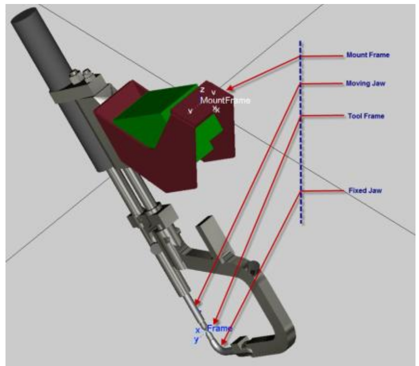

Figure 4-5 How spot weld gun is defined in the simulation software

Most of the spot weld guns have at least 3 home positions:

a. fully closed
b. semi opened
c. fully opened

Normally the spot weld guns are not servo driven but pneumatic driven. In offline pro-gramming there are several terms to be considered for the spot weld gun. There are two different types of speeds while spot welding, i.e. move speed and welding speed. Weld-ing speed is the speed by which the spot weld gun is performing the spot weld operation (open/close) and moving speed is the speed is the speed of the robot in between spot points.

So basically what happens in industry is that each robot station has its own spot weld tool. The stations are separated based on the type of operation going to be performed in each station. Also there are provisions for tool change (spot weld gun) in same station. In offline programming of robotic spot weld with the 3D Create software each spot point contains the information of the tool definition that means each spot point is as-signed with the tool name.

In consideration to the hardware properties of spot weld guns, among pneumatic-hydraulic-servo the pneumatic type mostly used for a lighter and uniform electrode. Hydraulic force is used in case of limited space and high force requirement. Also the spot weld guns can be conventional design, custom design and new generation. The conventional designs are the ones mentioned at the beginning of this chapter, custom ones also basically similar to the conventional one’s, the difference is in dimensions and to develop some new kinematics for the newer type. New generation spot weld guns mostly based on a modular concept to reduce cost and increase efficiency. An example is the 3G spot weld guns from ARO welding technologies. They have made 3G spot weld guns which are in 9 shared modules, 7 specific modules and 2 plug and play arms .

Parameters associated with spot welding

There are several parameters that are very important in the robotic spot welding process, incl:

- Open position: Defines the stroke length/angle of the moving arm when the gun is considered fully open.
- Close position: Defines the stroke length/angle of the moving arm when the gun is considered fully closed.
- Semi open: Defines the stroke length/angle of the moving arm when the gun is moving in between close proximity spot point.
- Weld Delay: The time the arms will be in closed position while spot welding.
- Tip Pressure: The amount of pressure the tip of the spot weld gun will generate while welding.
- Voltage: To set and alter the spot weld gun’s voltage value as necessary.

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There are no universal standard for parameters for the defining a spot weld. Different spot weld companies have their own parameters and the list can be pretty lengthy. But the points mentioned above are the most essential and basic ones.

4.2. Spot Welding Line Setup

4.2.1. Macros for reading/writing spot welding data

As per the target of thesis work an Add-on was developed by using Python API of 3D Automate to implement robotic spot welding. There were several challenges. To start from the basic modelling of parts in various CAD modelling software (Auto CAD, Solidworks, CATIA etc.) and then to understand the way how spot welding data is as-signed to those parts. After that to make the spot weld information readable to 3D Au-tomate an example platform was developed. This is basically a COM add-on coded with C# to read the spot weld data from a part in 3D Automate and write them to CSV file in an order. This was done to demonstrate a use case. Practically the target is to develop a macro for each widely used external CAD software and write the spot weld data's to a CSV file in a standard format which can be read by using the developed Add-on [SpotWelding] and assign spot welding points in the same CAD file in the *.vcm file which is the CAD file extension name for 3D Automate. In Appendix 1 there is an ex-ample of an excel file which contains the spot weld data's in a CATIA part. This excel file has been created by using own developed macro by one of the OEM's of Visual Components Oy.

There are many companies who have developed their own macro on top of software like AutoCad, SolidWorks or CATIA to export spot weld data's from the CAD model to Excel or CSV file.

4.2.2. Setup of Spot Welds in CAD model

The Add-On [Spot Welding] has been made in such a way that the spot welding can be implemented in the CAD model in 2 different approaches.

The Add-On can read *.csv files and to create frames in the component. Then these frame positions and orientations are used to generate the RSL motion statements in the spot welding robots. The second approach is that the spot weld points are already available in the CAD model itself as Geo feature. So the add-on can read the position matrix of those spot weld Geo features and then generate the RSL motion statements.

In case of reading spot weld data from the *.csv file and creating frames in the spot welding workpiece, first the position matrix of the root node of the component is grabbed. Then from the root node of the component the position matrix of the frame for spot welding is calculated and assigned. There are always several parts for spot welding; they are represented as separate features in the same component. It makes a lot easier to follow the parts and just focus on the spot welding job.

The parts (GEO_FEATURE's) which will be spot welded in different stations can just be made visible by signal com-munication, so the offline programmer doesn't have to worry about handling different components or visualizing the incoming flow of different spot welding parts in the sim-ulation. In the testbench the car BIW is set on a carrier which is fed through different spot welding stations via conveyors.

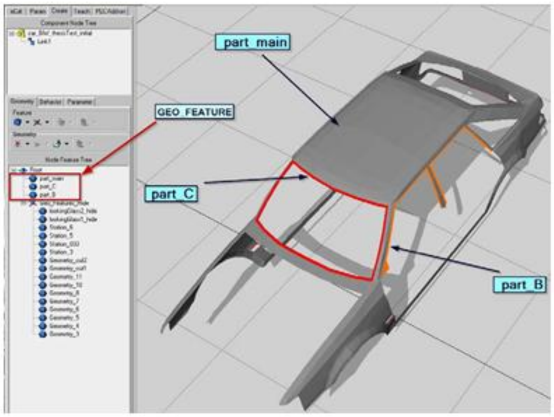

Figure 4-6 Car BIW CAD model for spot welding

A number of spot welds were grouped under certain group and these groups were named so that it will be easier to recognize the correct robot for a certain group of spot welds. If the car body is cross sectioned to four areas from top view then the first group of welds in the car is the bottom left section of the car, then the user has to think the consecutive group of welds clockwise. In this approach the 2nd, 3rd and 4th group of welds are presented in figure :

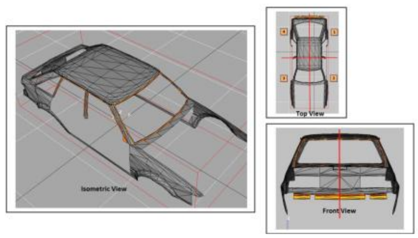

Figure 4-7 Cross section of CAR body for spot welding

4.2.3. Planning the Spot Welding Assembly Line

In this test bench a car BIW spot welding line was designed where there are three dif-ferent spot welding stations in series. Each station was assigned with four spot welding robots. Also a general rule was assumed to identify each robot in each individual sta-tion. In every station towards the direction of movement spot welding model (car BIW in this case) the robot on upper left side is considered the first robot in the station. Then the other robots are counted clock-wise as 2nd, 3rd and 4th robot of that station consecu-tively. In the test bench if the StationID of a group of spot weld is Station_3_1 that means this group of spot welds belongs to the 1st robot in the 3rd station. The screenshot of figure 4-17 shows the robotic spot welding line testbench more elaborately:

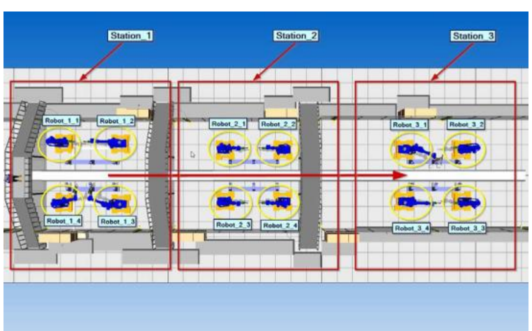

Figure 4-8 Robotic spot welding line setup.

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4.2.4. Features of the Add-On [SpotWelding]

In the manufacturing industry CAD modellers usually models the CAD geometry with the spot welding points included as small geometry features. This makes the OLP job a lot easier as the tag point for robot can be easily created from the CAD data directly. Here in the car BIW model there are almost 150 spot weld points which are represented by small circular geometry features.

To run this AddOn a robot needs to be selected first. When the user runs this AddOn the name of the selected robot pops up in the box [Selected Robot's Name]. Then the user has to enter the name of the station for which the selected robot is going to generate the RSL statements for the spot welding operation. While the geo spots were created in the car BIW CAD model it was kept in mind that there are four robots in each station and the spot welds were grouped in a way so that the reachability of spot weld points in each robot in each station are conveniently distributed.

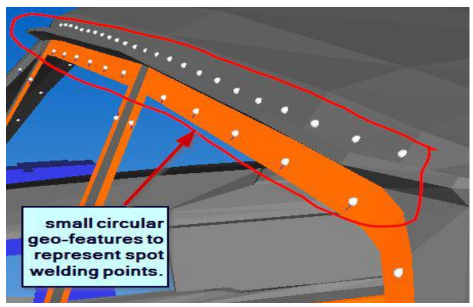

Figure 4-9 Geometry feature pointing spot location

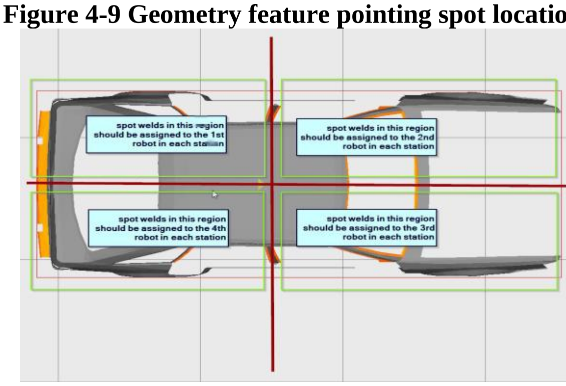

Figure 4-10 Distribution of spot welds according to robot position

V. CHAPTER5

5.1. Demonstration

In this chapter the working principle of the developed AddOn [SpotWeld] is discussed. A line consisting of three robotic assembly stations with each station consisting of four Motoman MS210 robots are set in the virtual environment. This automotive assembly line didn't take into consideration the details of part transfer, fixture assembly and in-termediate process. The main aim is to provide an overview of the proposed spot weld-ing tool.

5.1.1. Robot Selection

The robot which was selected for the spot welding line in this thesis work is a new gen-eration spot welding robot MS210 from Motoman. It is claimed to be the next genera-tion ultra-fast, high-density robot for spot welding application.

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Features of this recently released robot are given below :

- Ultra fast operation with new vibration control feature. By implementing new lightweight components the joint speeds has been increased 25% and cycle time decreased 30% from previous models. In future by utilizing new sensor free learning control feature cycle time can be reduced by more 10%.   Gas balancer has been implemented in joint-2 reducing the robot width by 25% and the robot base also been reduced by 43% from previous models. This has made the robot highly recommendable for high density installation.
- It has a high payload of 210 kg, which makes possible to use large spot weld guns. It has only one power cable, instead of 2 power cables in the previous model.
- It has advanced spot welding functionality which comes with the new controller DX200. It has automatic spot weld gun tuning feature for guns with different

5.1.2. Simulation of the Spot Welding Line

The spot welding line was implemented for a car with 3 different parts to be spot weld-ed by utilizing three spot welding stations and each station having four spot welding robots. The car frame has three different parts which are going to be spot welded in the line. By utilizing the developed AddOn-[SpotWelding] the RSL statements have been created in the robots. There were nearly total 156 spot welds in the whole simulation. In the sequence the car part comes on a carrier to the spot welding station and the conveyor gives an output signal to the robots that the part has arrived. After that each robot gives an output signal to the conveyor to stop. The spot welding operation starts and after completion of all the spot welds the robot gives an output signal to the conveyor to start again. When the conveyor gets input signal from each of the robot’s in one station it starts and the carrier (which carries the car part) goes to the next station. The spot welds are created by using the AddOn-[SpotWelding]. Both the functions of creating RSL from the CSV file or creating RSL from geometry features were used to demonstrate the functionality of the AddOn. There are several parameters that count for the cycle time of spot welding:

- ♣ Speed of conveyor
- ♣ Speed of servo of spot welding gun
- ♣ Motion/path planning
- ♣ Synchronous and non-synchronous movement of the robot and spot welding part
- ♣ Time of each spot weld
- ♣ Reachability and joint configuration.

The whole simulation which included all the 156 spot welds in three different station and 16 spot welding robots takes 4 min only. The variables in the spot weld gun are a major factor in the cycle time. Those are:

- ♣ Stroke speed
- ♣ Weld Time
- ♣ Voltage
- ♣ Tip Pressure
- ♣ Synchronous motion with the external axis
- ♣ Complexity and distribution of the spot welding points.

The AddOn [SpotWelding] is based on a CAD based approach. This tool enables the user to work on the CAD file, define welding path and approach escape path between two consecutive welds, organize the welding sequence. When the definition is complete the designer can export all the spot welding data to an external *.csv file using the de-veloped COM application [CreateCSVspot] which is written in C#. This tool extracts all the spot weld information from the CAD file and creates the *.csv file. After that utiliz-ing the tools in the AddOn the user can extract information from the CAD file or the *.csv file and create robot command (RSL statements) and can be immediately tested for detailed tuning. Then utilizing the modifying tools in the AddOn there can be neces-sary modification, correction of the spot welding parameters. After a few simulation, checking collision points and robot movement paths needs to be updated, speed updat-ing for different inter process points for faster operation it needs tuning of the robot program and the whole robot program in RSL is ready to be converted to robot specific (in this case Motoman MS210) program by using the OLP tool. The whole process can take from a few minutes to few hours depending on the complexity of the process

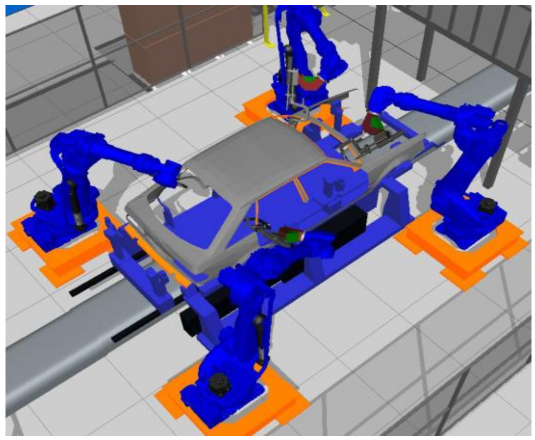

Figure 5-1 One Station with four spot welding robots

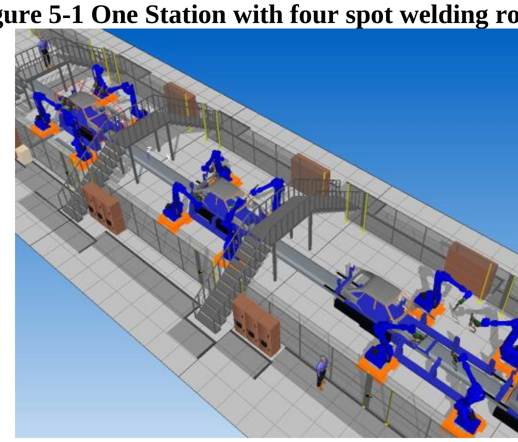

Figure 5-2 Isometric view of the spot welding line

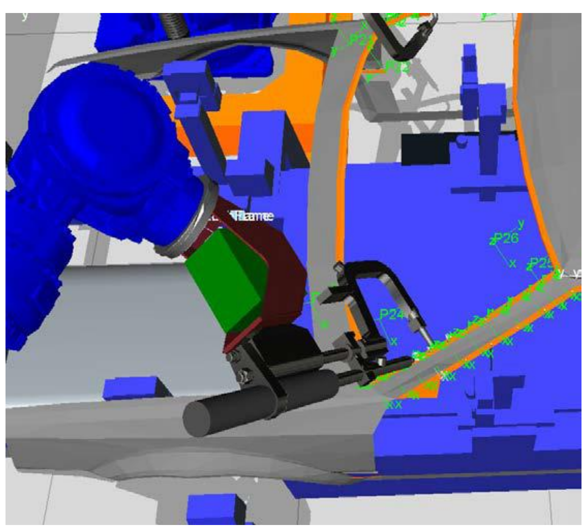

Figure 5-3 Close view of the spot welding operation

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5.2. Simulation Result

The aim of the developed AddOn > [SpotWelding] was to make a closed loop solution for the automotive spot welding line. In previous practice while doing the spot weld process planning only one station was kept in consideration and then there was not enough feedback from the system to quickly make compensation or update in deviation the CAD geometry or the assembly

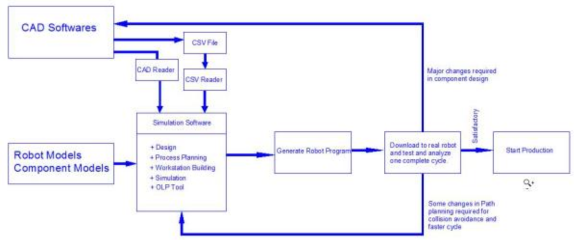

Figure 5-4 Proposed method for a spot welding assembly line

A spot welding line in virtual environment was made in 3D Automate and consisted of three assembly stations and each assembly station with four Motoman MS210 robots. In previous practices the storing and interchange of spot welding data were ignored. A method is proposed here which can be described in following steps:

- The CAD software (AutoCAD, Solid Works, CATIA, ProE etc.) generates the model of the assembly of the car body
- The details of spot welding operation are taken into account and the data are stored in 2 ways: a) In the CAD file or b) In a separate CSV or Excel file.
- As different CAD modellers may generate different kind of assembly infor-mation so there needs to be an intermediate converting AddON which will inter-pret the spot welding data and import the information in the simulation software.
- CAD readers makes it possible to import almost all the different CAD for-mats(Step, Igs, dwg, CATIA, SolidWorks etc.) to the simulation software. If the CAD files contains the spot weld data inside then these are also imported.
- The robot workcell environment is created (by using point cloud or imported CAD model) in the simulation software.
- The workcell is calibrated.
- The assembly parts are placed on the fixture and taken to the assembly station where the developed AddOn [SpotWeld] is used to generate the robot program.
- As path planning was done without any collision avoidance algorithm so the PTP (point to point) motions were directly assigned.
- Manual touch up and PTP motions needs to be added to the robot program to avoid collision with the assembly part and the neighbouring robot.
- Simulation is run and checked if right spot weld task was assigned to the right robot in the right assembly station, if not the AddOn facilitates to quickly delete the current faulty program and generate the spot sequence correctly again.
- A closed loop method is proposed which starts from the as CAD design and goes through the 3D process simulation , trajectory planning and finally the ro-bot the program is uploaded to the real robots in the factory floor.

VI.   CHAPTER-6

WAY-FORWARD (PHASE – II)

Proposed methodology to SIMULATE THE SPOT WELDING ROBOT.

This project will continue to focus on developing an SIMULATION process by the below described approach, which integrates both modeling and simulation.

5.1 Spot weld distribution

Stage 1: Allocation of weld spot count for each robot

Stage 2: Confirmation of panels

5.2 Gun Validation

Stage 4: Gun Confirmation of each robot

Stage 5: Gun types needs to confirm

5.3 Layout confirmation

Stage 6: Confirm the tip dresser position

Stage 7: Equipment location

Stage 8: Robot Location

5.4 Path Creation

Stage 9: Have to confirm the optimized weld order

Stage 10: Create the optimized the path generation.

Stage 11: Weld action settings.

5.5 IO signal confirmation

Stage 12: IO signals for each robot.

Stage 13: Interlock signals for each robot required

5.6 Cycle time confirmation

Stage 14: Cycle time

5.6 Robot code conversion and output documents.

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