2017

Design of an Adaptable Tooling System for Part to Part Variation Processing

Boris Novakovic
University of Windsor

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By

Boris Novakovic

A Thesis
Submitted to the Faculty of Graduate Studies
through the Industrial Engineering Graduate Program
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada

Design of an Adaptable Tooling System for Part to Part Variation Processing

By

Boris Novakovic

APPROVED BY:

____
R. Bowers
Mechanical, Automotive, & Materials Engineering

____
A. Djuric
Mechanical, Automotive, & Materials Engineering

____
W. ElMaraghy, Co-advisor
Mechanical, Automotive, & Materials Engineering

____
H. ElMaraghy, Co-advisor
Mechanical, Automotive, & Materials Engineering

May 3, 2017

DECLARATION OF PREVIOUS PUBLICATION

This thesis includes one original paper that has been previously published in conference proceedings, as follows:

Thesis Chapter	Publication title/full citation	Publication Status
3 & 4	Novakovic, B., ElMaraghy, W., & ElMaraghy, H. (2017). Design of an Adaptable Tooling System for Part to Part Variation Processing paper presented at the IEEE conference on Controls & Robotics, Windsor, ON	In Press

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ABSTRACT

Today's automotive manufacturing facilities use different robotic systems with the specifically designed end of arm tooling (EOAT). Regardless of how accurate these robotic systems may be, they are programmed to repeat the same task and move to the same position repeatedly. As convenient as this process may be, it does not allow robots to automatically readjust to different part variations without the human assistance. This situation is especially noticeable in the plastics manufacturing industry, e.g., fuel tank welding.

This thesis describes the systematic design methodology of an adaptable tooling system for a part to part variations processing aimed at automotive plastic fuel tank manufacturing. By combining a 3D vision system with a PLC, and a Fanuc R-2000iB/165F 6 axis robot, the system provides the robot with the ability to automatically readjust the processing unit to different part variations.

The design approach specifies programming and device correlation by using Siemens S7, Fanuc TP, and SICK AG software. A case study using a fuel tank sample was developed to check the system for functionality and performance. Results of the study indicate that the system is accurate within ±0.25 mm, which is well suited for fuel tank manufacturing.

The study signifies a new approach to vision guided robotics (VGR). It utilizes existing equipment for applications where part variation may be present.

Three patent applications were published during the course of this research. They each cover plastic fuel tank welding applications.

DEDICATION

To my family

To my fiancée Jayde, for her encouragement and support

ACKNOWLEDGMENT

I would like to express my sincere gratitude to my supervisors Dr. Hoda ElMaraghy and Dr. Waguih ElMaraghy for providing me with the possibility to complete this thesis research. I cannot thank you enough.

I would also like to thank everyone at the IMS Centre for their assistance and support during the course of this research. A group of truly amazing individuals with whom it was a pleasure to work.

I am also indebted to SPM Automation (Canada) Inc. for their support, cooperation and equipment access, without which this research would not be possible. Thank you for all those times you supported me when I had to leave work to go to class or study. Special thanks go to Mr. Chris Holtkamp, Mr. Nikola Zubic and Mr. Cory Lane for their valuable assistance during the course of this research.

Finally, I would like to thank my fiancée Jayde, for being my cheerleader and supporting me when I needed it the most. Thank you for believing in me.

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NOMENCLATURE

6 DoF	Six Degrees of Freedom. Describes robot freedom of movement.
5 DoF	Five Degrees of Freedom. Describes robot freedom of movement.
Com	Communication Values
DI [ ]	Digital Input
DO [ ]	Digital Output
EE	End Effector Connector
EOAT	End of Arm Tool
HMI	Human Machine Interface
IDEF0	Icam DEFinition for Function Modeling. ICAM is an acronym for Integrated Computer Aided Manufacturing
I/O	Input and Output
ISO	Isostatic
LBL	Robot Label
M	Measured Values
mm/sec	Millimetres per second
OEE	Overall Equipment Effectiveness
PLC	Programmable Logic Controller
PR[ ]	Position Register
R [ ]	Robot Register
Ref	Reference Values
RI [ ]	Robot Input
RO[ ]	Robot Output
ROI	Region of Interest
SC3DTM	Single Camera 3D Technology
TCP	Tool Center Point
TCP/IP	Transmission Control Protocol/Internet Protocol
TP	Fanuc Programming language used by Fanuc Robotics for robot programming
VGR	Vision Guided Robotics
WIP	Work in Process

CHAPTER 1: INTRODUCTION

1.1 Conventional Plastic Welding

In order to keep manufacturing systems in line with fast-moving pace of OEM demand, Tier 1 plastic suppliers are faced with a challenging request to keep the production lines at such pace. Any kind of alteration in the process will create the variation in part geometry, resulting in a need to readjust the processing units to the part (e.g. blow moulded plastic fuel tank). Depending on the process, this task may take long periods of time as once the processing units are adjusted, initially manufactured components are required to go through quality control prior to the manufacturing line continuing with the production. This provides motivation for the development of a machine system which should reduce waste, and increase efficiency and productivity, while preserving high value human involvement (H. A. ElMaraghy, 2009). Most critical weld are referred to as hermetic welds, which are commonly found in all components which provide fuel transfer to the inside/outside of the fuel tank; such as inlet check valve (ICV).

Figure 1-Inlet Check Valve

These welds are created by one of the most popular thermoplastic joining methods called hot plate welding. This method works by placing two components at the hot plate surface, whose surface is then heated by conduction to promote component melting. Upon reaching predetermined amount of melt at the molten surfaces, the heat source (i.e. hot plate) is removed and the two components are brought together. Two components are then held together and allowed to solidify producing the weld. A certain amount of weld flash created by the molten plastic is squeezed out of the joint assuring adequate fusion between the components (Grewell & Benatar, 2003).

Processing units used for this welding operation are referred to as the Fusion Units. Controlled by the closed loop control system, these units are equipped with multiple sensors for position and force monitoring. They consist of different subassemblies such as Component Gripper which is used to retain the part being welded to the fuel tank, Part Hot Plate used to melt the component welded to the fuel tank shell, and Tank Hot Plate assembly used to promote the melt on the fuel tank surface. Figure 2 illustrated this unit.

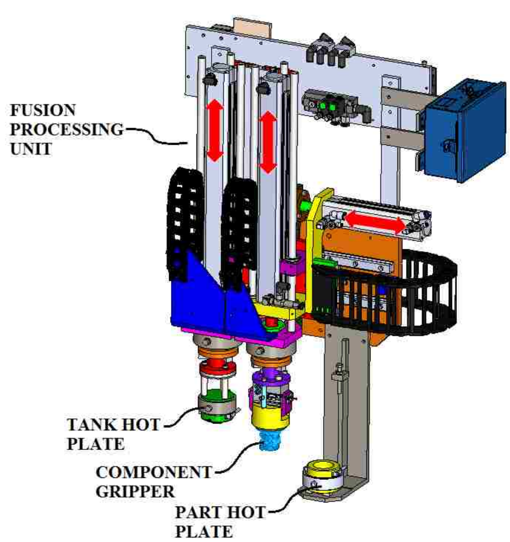


Figure 2-Fusion Unit Assembly Illustration (Courtesy SPM Automation (Canada) Inc.)

Fusion Units are normally guided to the fuel tank area by linear slide or robot, from which point welding process takes place. Tank Hot Plate is brought into contact with the fuel tank, at which point simultaneously Component Gripper is advanced to the Part Hot Plate, promoting the part in the Component Gripper to melt. Once both melt pools are created, Tank Hot Plate is retracted from the fuel tank, Part Gripper is retracted from the Part Hot Plate, and melted part is brought into the contact with the melted surface on the fuel tank, followed by solidification process.

The task of processing unit readjustment is typically performed by maintenance technicians and is usually required every time a different batch of parts is introduced (i.e. WIP, change-over, rework parts, etc.), part of the process is altered, or even air moisture content is changed due to the outside temperature. All these factors can result in component or component feature location to change position and/or shape.

This chapter will discuss robotic and fixed processing units commonly found in plastic fuel tank manufacturing systems. It will also cover the need for automatic adjustment systems.

1.1.1 Welding Process Steps

It is imperative to understand the plastic welding phases/steps in order to convey the impotence of this research. Following plastic welding phases are defined by (Grewell & Benatar, 2003).

<u>*Matching*</u>: is the initial stage of the plastic welding process which requires increased force applied by the hot plate (controlled by load cell) in order to conform the fuel tank surface to the hot plate geometry. This process eliminates normally found surface deformation (such as flatness) and allows for the weld surface to create a uniform flat surface ready for

the heating stage. Displaced material is incorporated in the flash past the hot plate perimeter. Time for this stage is determined experimentally usually by trial and error until the desired result is achieved.

Heating: is the second part of the heating process which starts immediately after the matching stage without any mechanical movement of the processing unit. The force of the hot plate during the matching phase is decreased to a minimum (controlled by load cell) and the surface is allowed to be melted without any material displacement (energy is transferred through conduction heat transfer). Heating time may be determined theoretically or experimentally and checked through the microtome process (Wikipedia, 2016a) until heat affected zone of 0.4 mm is achieved.

Change-Over: is the mechanical movement of the parts at the end of the heating phase, which occurs by moving each part out of the contact with the respective hot plate. In the fuel tank welding, tank hot plate is removed for the fuel tanks surface, respectively retracting the component gripper form the part hot plate. This is followed by the position change of the tank hot plate cylinder and the part gripper cylinder, positioning the part gripper directly over the melted fuel tank surface and bringing the melted parts together. Change-Over time should be kept under 5 seconds for high-density polyethylene (HDPE) welding in order to avoid surface cooling of the melted components.

Fusion: is the last stage of the process. It refers to parts being placed in contact together under pressure and allowed to cool and solidify, completing the welding process. Joining pressure is monitored by the load cell in order to assure that the correct amount of melt is squeezed into the weld flash around the component. Having the pressure set too low during the fusion stage will not allow for entrapped air to be removed and provide intimate contact between the components at the weld interface. Further, having the pressure set too high will squeeze all the melt out of the joining area, creating an effect called "cold weld" (virgin un-melted materials are below the melting point and act as a stop) resulting in a weak weld.

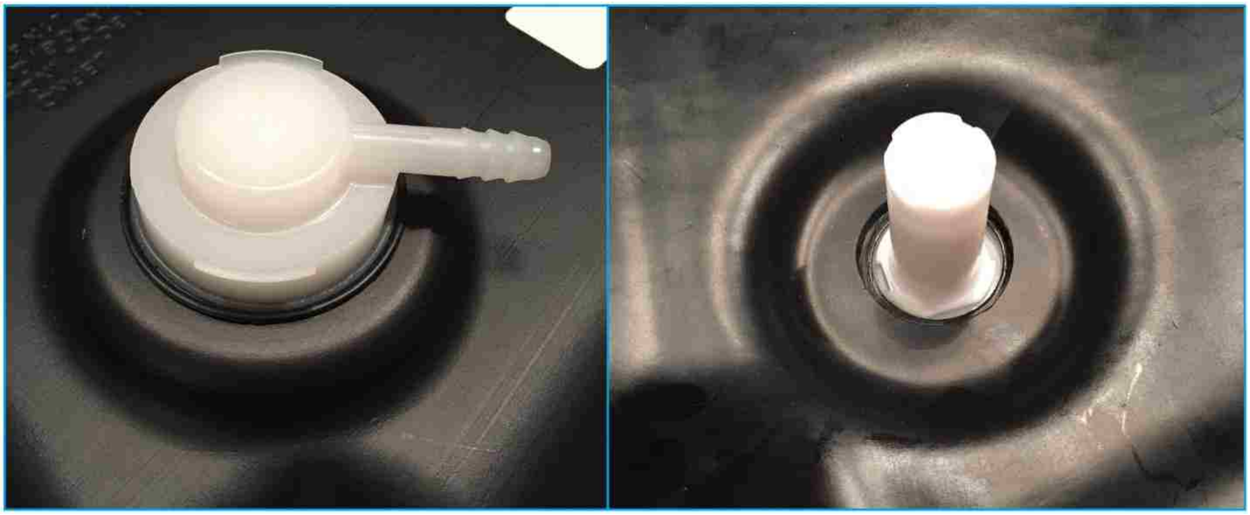


Figure 3-Outside and Inside Image of Component Properly Welded to Fuel Tank Body

1.2 Hard Fixed Processing Units

Dedicated production lines are commonly equipped with the fixed processing units composed of the Fusion Unit attached to the machine frame via adjustment unit. This allows the Fusion Unit adjustment in 3 major and 3 minor axes to the fuel tank surface, resulting in tank hot plate being able to conform to the center of the feature and provide parallel rectification of the hot plate to the hole weld surface. The process begins by the fuel tank entering the station and clamping in the tank fixture. Once clamped in the tank fixture, the processing unit is advanced usually by a linear slide, followed by the welding of the component to the fuel tank surface which seals the hole opening. This conventional process is often referred to as "blind" welding, meaning that the sensors and load cell on the processing unit are used to assure that the contact between the processing unit and the fuel tank is made, without monitoring the accuracy of finding the correct location and parallelism to the weld surface. Once the operation is completed, the weld seal/quality is checked in the helium leak station (the process performed later down the line) where the fuel tank is tested for hermetic seal once all the components have been welded.

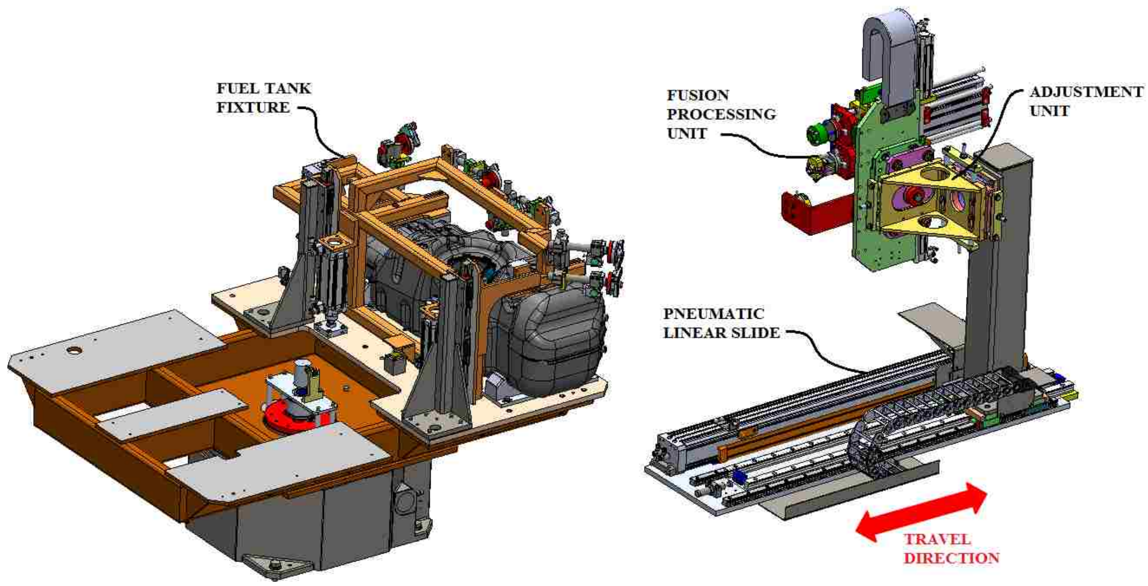


Figure 4-Fixed Mounted Fusion Unit Position Relative to the Fuel Tank Fixture (Courtesy SPM Automation (Canada) Inc.)

1.3 Robotic Processing Units

Robotic production lines are normally equipped with the same Fusion Unit as dedicated equipment. This unit is used as EOAT which is attached to the robot 6^{th} axis. These robotic configurations are found either as stand-alone cells or as a part of the larger production line (e.g. index table or linear transfer production line) in the manufacturing settings. In either case, once the fuel tank is clamped in the tank fixture, the processing unit is advanced to the feature of interest by the robot, in order to perform the welding operation. Regardless of the processing unit being mounted to the robot or the mechanical adjustment unit, the process is still considered “blind” welding since the sensors and load cell is used to provide the feedback that the contact is made and the weld is performed.

The advantage of having the processing unit mounted on the robot over the mechanical adjustment unit, is in the position re-adjustment time. Recording the new robot position is much faster and easier than mechanically trying to adjust the processing unit to the fuel tank surface.

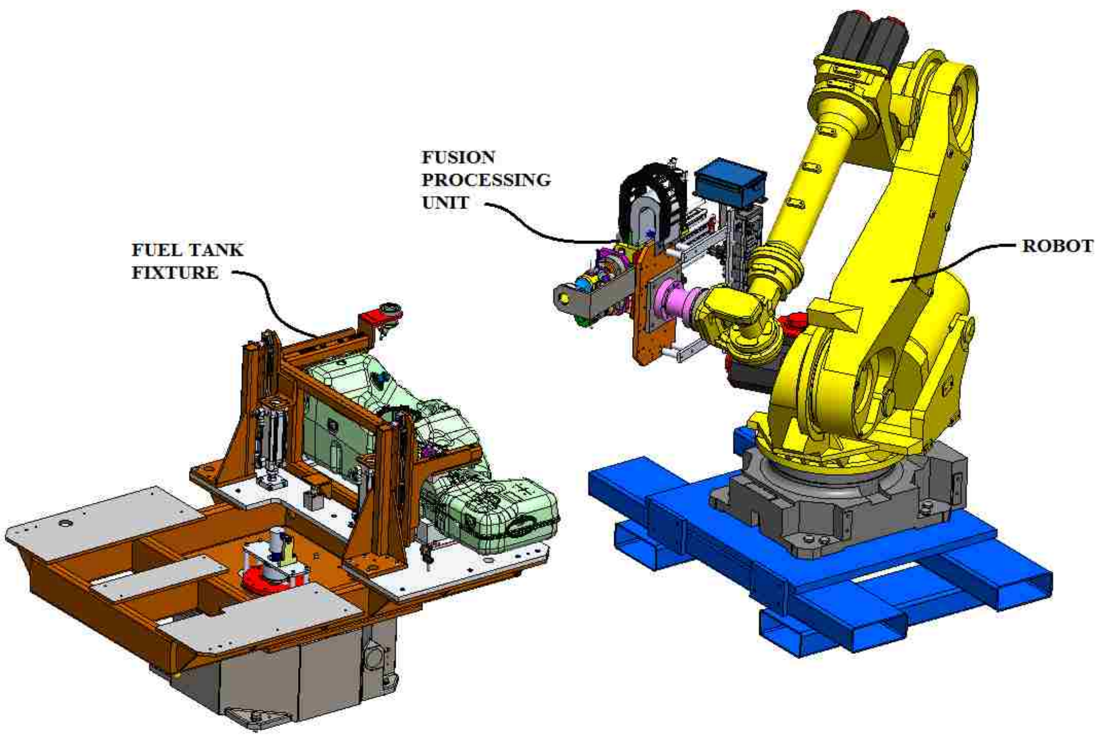


Figure 5-Robot Mounted Fusion Unit Position Relative to the Fuel Tank Fixture (Courtesy SPM Automation (Canada) Inc.)

1.4 Current Industrial Practice

In order to understand why the part variation occurs in the automotive fuel tanks and the need for this application, research needs to briefly describe the manufacturing process. As automotive fuel tank with the typical shrink rate of 4% is used in the case study, this section will discuss the shrink control, direction, and datum points of the fuel tank. Considering the component length of 1.4 meters as outlined in the example below, length deviation of 5.6 cm in overall length can be expected from the blow moulding process to the final pack-out stage when the fuel tank should stabilize to room temperature. However, since the welding process is performed about halfway through the production, shrink rate is still very active and part variations can be observed (comparing work in progress to already cooled fuel tanks) during the welding stage. To overcome this issue, manufacturers design and utilize datum geometry on the fuel tanks commonly referred to as the isostatic (ISO) locator features. Typically, there are 2 ISO features on the fuel tank; 4-way constraining the part location in two directions and 2-way constraining the part in one direction. Combined together, these features control the geometry of the fuel tank during the shrink stage in the welding process. ISO features are also used as the datum points to measure the compliance of the final product, i.e., fuel tank, to the vehicle body.

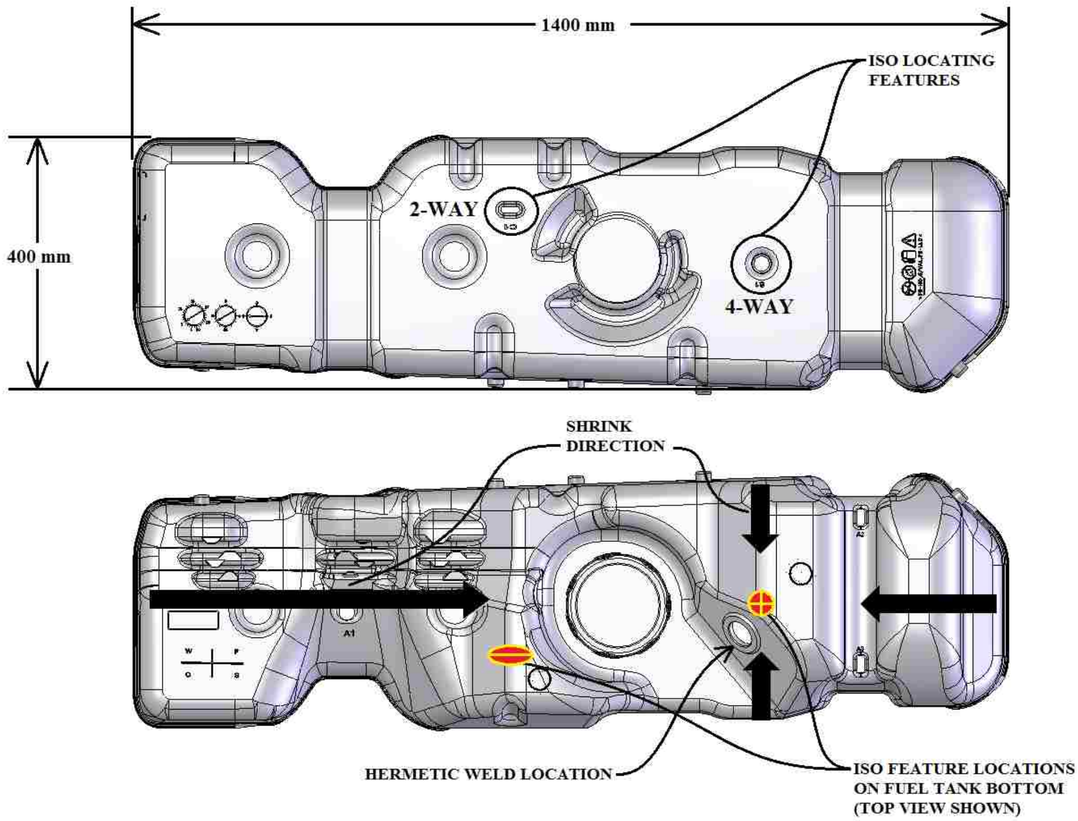


Figure 6-ISO Feature Location on Fuel Tank

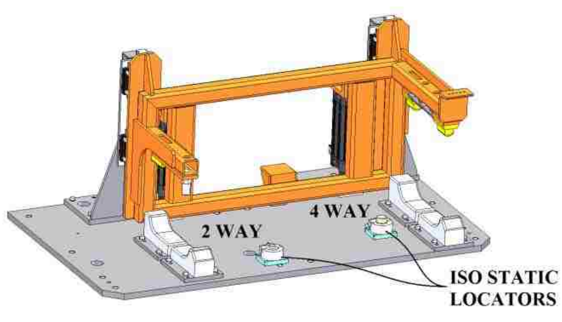


Figure 7-ISO Pin Assembly on Tank Fixture (Courtesy SPM Automation (Canada) Inc.)

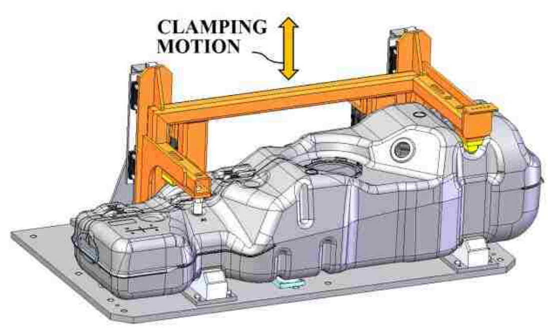


Figure 8-Fuel Tank Clamping (Courtesy SPM Automation (Canada) Inc.)

As illustrated in the figures above, fuel tank fixtures used in the welding process contain assemblies designed as the reverse side of ISO features, called "ISO Pin" assemblies. These assemblies are part of a typical tank fixture design in the fuel tank welding industry. Combining ISO feature on the fuel tank with the ISO pins on the tank fixture provides consistent fuel tank location in the tank fixture relative to datum locations. However, as the shrink factor is still active and the fuel tank is still changing in terms of geometry, shrink magnitude may move through the 2-way ISO towards the 4-way pin in the tank fixture as shown in the figure below.

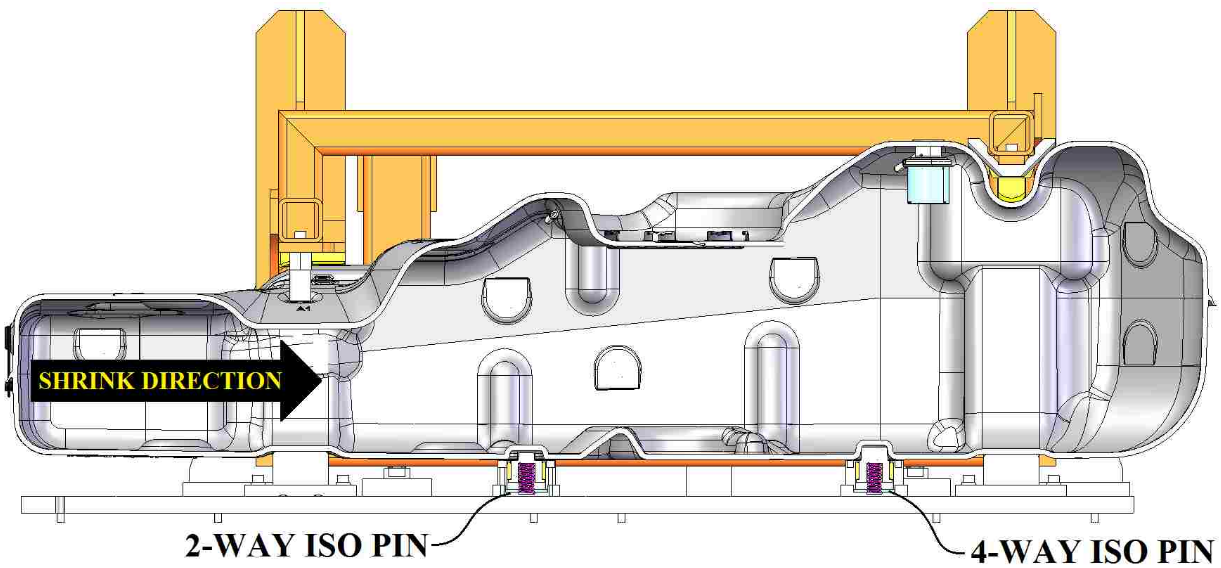


Figure 9-Fuel Tank fixture Cross Section (Courtesy SPM Automation (Canada) Inc.)

As mentioned earlier regarding the process stability and the fuel tank variation during the welding process, Figure 10 below illustrates a 2-way ISO pin assembly designed to allow a variation in position of fuel tank 2-way ISO feature within ±10 mm.

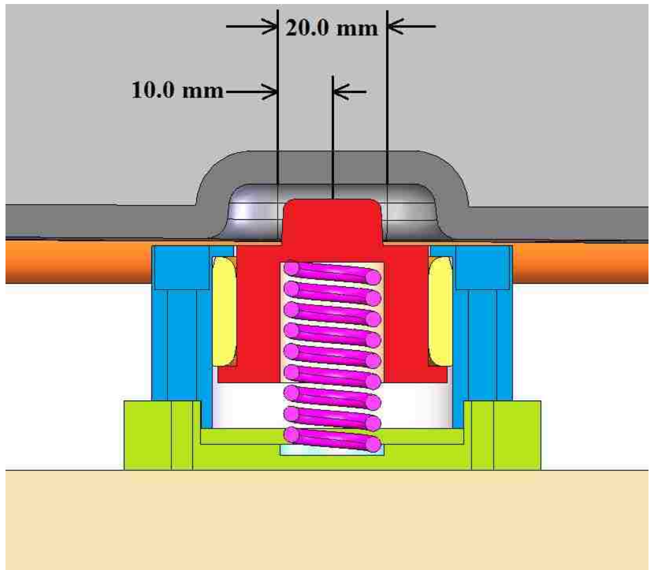


Figure 10-2-Way ISO Pin Assembly Cross-Section (Courtesy SPM Automation (Canada) Inc.)

To conclude above-mentioned details, ISO structures drive the fuel tank manufacturers to position all hermetic welds in close proximity to 4-way ISO feature in order to eliminate feature location variation driven by the shrink. This in return constrains the fuel tank geometry design and configuration of the fuel tank. Therefore, it is common to find all hermetic welds in close proximity to the 4-way ISO feature, as locating hermetic seals in more remote locations from the 4-way feature will result in constant equipment adjustment and increased scrap rate.

Other factors such as manual handling of hot blow moulded fuel tank by manual de-flashing operations and transferring the part to the next process contribute to the fuel tank geometry variation as well; however, this will not be covered in this study as the research will only concentrate on the non-operator dependent processes.

1.5 Research Motivation

As some part to part variations are acceptable in the mass-production manufacturing process, others may not be. Regardless of the use in dedicated or flexible manufacturing production lines, processing units are designed to come in contact with the fuel tank surface and weld the component. This position is adjusted by maintenance or setup technicians and therefore it is always in fixed orientation and position relative to the fuel tank. And while fuel tank surface might change, the processing unit will always advance towards the same position in 3D space. Even though force sensing and monitoring is an integral part of the closed loop controls system which monitors the welding process, the result of the welding operation is that the components are welded to the fuel tank surface without knowing if the correct position and/or angle to the weld location are attained. Aside from the component being welded out of concentricity with the feature (Figure 11), this also may cause damage to ethylene vinyl alcohol (EVOH) layer (Figure 13), if the hot plate surface on the processing unit is not parallel with the hole weld surface on the fuel tank. Figure 12 displays a component welded out of angular adjustment.

Figure 11-Part Welded Out of Concentricity

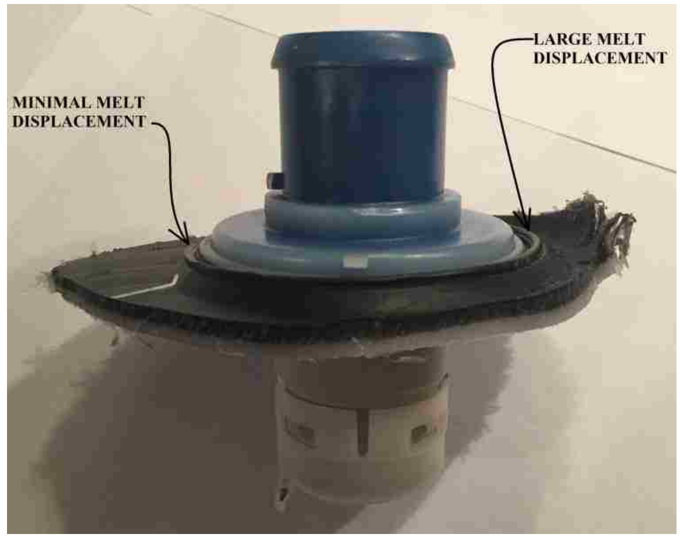


Figure 12-Part Welded on an Angle

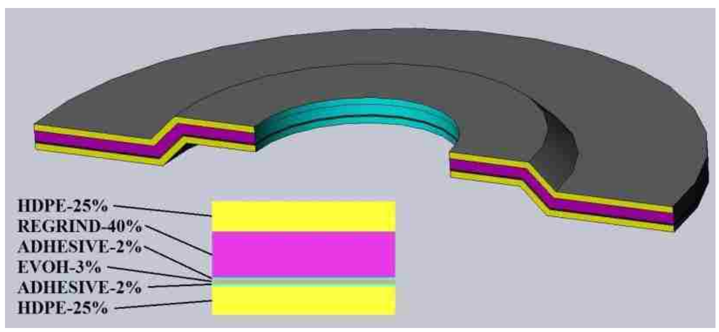


Figure 13-Fuel Tank Blow Moulding Layers

EVOH layer consists of 3% overall fuel tank wall surface and is used as a hydrocarbon barrier to prevent volatile gasses from escaping through the fuel tank wall (SIMONA, 2010). Though it is located closer to the inside wall of the tank surface, EVOH layer damage may become undetected during the manufacturing process if an angular mismatch between the hot plate and the tank surface becomes evident as shown in Figure 12.

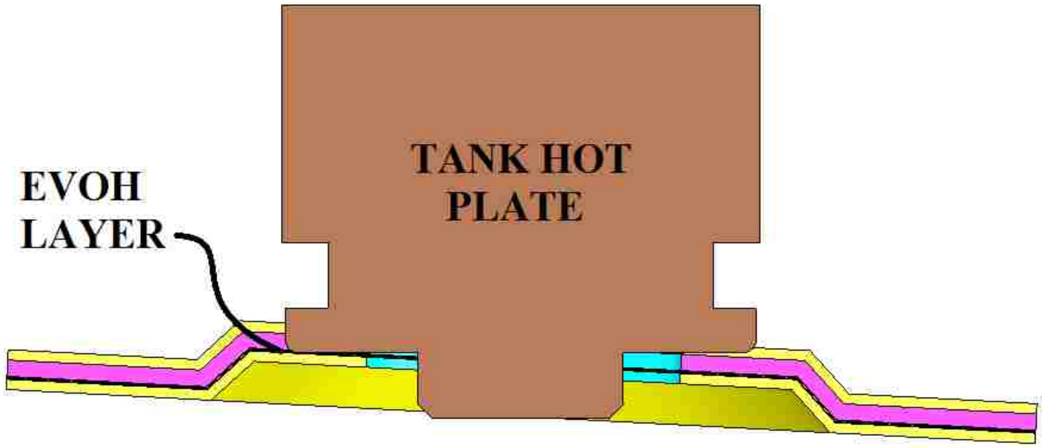


Figure 14-CAD Representation of Misaligned Melt Phase

Figure 14 illustrates the incorrect welding position of the component shown in Figure 12.

1.6 Objective and Problem Statement

The objective of this master thesis is the design and introduction of a new method for adaptable tooling system which would automatically adapt to part variations, especially noticeable in large automotive plastic fuel tanks.

By doing so, the research will be able to create a methodology for establishing a relationship between the system components, as well as their function. Currently published literature is unfortunately limited in terms of systematic design approach regarding robotic guidance systems, due to the proprietary nature of these systems.

By finding the correlation between the image captured by the 3D vision system and the 6 DoF robot in 3D space, the system would be able to reposition the EOAT to the feature of interest in the image every time the position change would occur.

The equipment selected for this work is SICK AG IVC 3D vision system, Siemens PLC, and Fanuc R2000-iB/165F robot equipped with an end of arm tool for plastic welding.

The significance of this design is aimed to improve OEE (Overall Equipment Effectiveness), eliminate scrap rate, simplify equipment/machine design, minimize maintenance personnel, and decrease the cost of manufacturing by eliminating inconsistencies.

The intent of this work is to allow for other manufacturing applications where the part to part variation is present, to implement the presented design where part variation or component positioning may have an impact on the production quality.

1.7 Thesis Outline

Chapter 2 will conduct a literature survey on academia, patents, state-of-practice, and state-of-the-art, as this research is directed more towards the industrial applications. Chapter 3 will review the systematic design approach in terms of methodology and IDEF0 modeling. Chapter 4 will present a case study example which will define design details with examples. In Chapter 5 the research will demonstrate the results and the validation of the system, which will be followed by system benchmarking. Chapter 6 will encompass discussions, conclusion and future work on the system.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

The study of vision-guided robotic systems using different tools has been a topic of interest in both manufacturing industry and academia. As such, this chapter will encompass different sections relating the research to academia, patents, state-of-the-practice, and state-of-the-art.

The first part of the chapter will encompass the review of academic work, followed by the review of the existing industrial patents. The third part will cover the discussion on state-of-the-practice technique, followed by the discussion related to the state-of-the-art in the industry. Many journals and patents have been researched, however only the ones most related to this research have been cited and covered in this thesis.

2.2 Academia

This section will discuss research covered by academia related to vision-guided robotic systems.

(Šuligoj, Šekoranja, Švaco, & Jerbić, 2014) proposed object tracking with 2 robots and stereo vision cameras. The problem was addressed by using 3 points on the part pallets used to track the object with the vision system. The system was constructed by two cameras mounted on the first robot, while the second robot carried the markers. Camera robot would monitor the position of the marker robot and advise it on its position relative to the object by calculating the position between the robot's tool center point (TCP) relative to the part being processed. Communication protocol was established by using C++ programming and transmission control protocol/internet protocol (TCP/IP). This system shows a level of complexity as well as constraints. In order to make the system functional, markers described in the research must be present in order for the second robot to track the object and coordinate the position to the robot performing the operations. Without the markers, the system would not be able to perform, making it prone to failures. Authors presented a viable solution for robot guidance; however, the integration of the two robots in sync makes the system very expensive and intricate due to the synchronizing process.

(Bellandi, Docchio, & Sansoni, 2013) proposed using one robot and two cameras (one in 2D and second in 3D) in order to reposition robot to the object more accurately and faster. The camera is presented as a "stand-alone" device in the 2D, and combined with a laser slit projector in the 3D system operating in triangulation mode, it creates a system used for object location and fitting. Research describes the arrangement composed of both cameras fastened to the robot end of arm tool (EOAT). This concept arrangement describes a system where the 2D geometric template matches and classifies the 3D object in order to get a more robust and faster processing solution by eliminating the cloud segmentation and object classification. By excluding the point cloud, 3D data is used for calculating location as well as the object orientation in order for the robot EOAT to be properly oriented to the object/feature of interest. This system shows enough accuracy for pick and place applications, however it is constrained to objects with simplified shapes such as cylinders and flat surfaces (planes) and would have limitations in recognizing and analyzing objects which contain 3D surfaces (object height changing in Z direction) where multiple features would need to be identified and located.

(Martinez, Boca, Zhang, Chen, & Nidamarthi, 2015) research comprised of one robot equipped with the stereo camera for random industrial bin picking applications. The study describes the methodology on coordinate system synchronization between the two devices, meaning that any scanned object would have its position directly related to the robot. Each object is analyzed for access to picking position prior to robot advancement. Due to EOAT size, the system was required to use 2 tool center points (TCP), and develop a procedure for robot extraction path once the objects were grasped in order to avoid a collision. Research demonstrates teaching methodology for using two different tool center points (one for each part gripper on EOAT) and calibrating them together, along with other methods such as robot extraction. System indicated some limitations regarding the part orientation which was impacted by larger EOAT, as well as longer cycle time produced by the algorithm used for object location and positioning.

Another bin picking application was presented by (Oh, Lee, & Lee, 2012). This research describes the design of the system on the similar platform for pick and place application as (Martinez et al., 2015). Published paper defines the application where one robot and two cameras are used to locate the object. By using a larger field of view and geometric pattern matching method with the respect to the 2D image, this concept allowed for a more robust system which would be capable of locating components that would previously generate faults. Designed for industrial applications, the system incorporated collision avoidance by using the object orientation with respect to the bin orientation, increasing the system reliability. The system did show certain sensitivity to outside elements (i.e. lighting) which limited the system in high accuracy applications. After presenting the system at Korea Robot World in 2010 as well as 2011, the system showed great success and public interest.

(Semim, Jr, Silva, Silva, & Tormena, 2012) developed another concept on using the vision system for positioning the robot EOAT to the engine head which may vary in position and orientation. Computed vision system program was created by using Pearson Correlation (Yen & Johnston, 2005) to determine the object position and orientation. The correlation of the image and the robot EOAT was created by corresponding holes on the engine head to the tool center point on the EOAT. Change in engine head position (displacement position) was then transferred to the robot TCP position which would then be adjusted with the same displacement values.

Charge-coupled device (CCD) camera integrated with 5 degrees of freedom (5 DoF) robot was explored by (Xie & Hämmerle, 2008). Research selected somewhat limited 5 axis robot, equipped with the CCD camera on the end effector. To achieve the accuracy of the vision system, new image processing technique was developed by using a pinhole camera. Object recognition was performed by using 2D and 3D cameras; by taking images from different angles in order to achieve accurate object angle position. This at the same time eliminated the possibility of generating an inaccurate image and adjusting the EOAT incorrectly if clustered objects are present in the work envelope. In addition to this, the procedure used color instead of grayscale images, improving object tracking and registration. It is imperative to acknowledge that the experiment utilized kinematics in order to eliminate the vibrations created during the robot joint angles during the object scan, which resulted in improved scan path speed and more accurate image recording.

2.2.1 Academic Literature Review

Current academic publications relevant to this research were reviewed in the previous section. The approach used by the academia illustrates different methods of adjusting the robot end effector to part variations or differently positioned objects. The experiments performed include a well-defined systematic approach to providing object recognition and orientation in 3D space by using different robot arrangements in conjunction with single or dual cameras. By using existing or developing a custom cloud platform for object pattern matching the studies were tested for material handling (i.e. pick and place) applications.

Academic research identifies a level of complexity inadequate for manufacturing settings, as certain industrial components (such as PLC) are not utilized, and proposed custom programming software is often not recognized and/or approved by the industry.

Experiments displayed do not directly satisfy part processing applications (e.g. welding, screwing, trimming, etc.) by using a single robot in conjunction with a single 3D vision system and the PLC. However, methodologies displayed provide a good starting point that can be used to develop a new approach for developing such system.

Table 1-Academia Research Gaps

		Integration						Capability				Value				Details			
		Single Robot	Multiple Robots	Single Camera	Multiple Cameras	PLC Communication	Robot Communication	Position Adjustment	Inspection	Different Outputs	Integration Ease	Production Cost Saving	Quality Increase	Material Handling	Part Processing	Task Clarification	Conceptual Design	Embodiment Design	Design Detail
Academia	Šuligoj F. et al (2014)		✓		✓		✓	✓				✓	✓	✓		✓	✓	✓	✓
	Bellandi P. et al (2013)	✓			✓		✓	✓				✓	✓	✓		✓	✓	✓	✓
	Martinez C. et al (2015)	✓		✓			✓	✓			✓	✓	✓	✓		✓	✓	✓	✓
	Oh J. et al (2012)	✓			✓		✓	✓				✓	✓	✓		✓	✓	✓	✓
	Semim R. et al (2012)	✓		✓			✓	✓			✓	✓	✓	✓		✓	✓	✓	✓
	Xie S. et al (2008)	✓			✓		✓	✓				✓	✓	✓		✓	✓	✓	✓

✓	-Explored
	-Not Explored

2.3 Patents

(Richard, 2008) wrote an article on robotic guidance where he mentioned that marriage of vision and robotics is changing the robotics nature, by going from pre-programmed directions to the robots which are starting to “find their way” in a manufacturing environment. This can commonly be observed at the robot conferences and/or shows, which is usually followed by the industrial pretense. And even though most of the manufacturers and/or integrators are very secretive regarding the methodology on the robotic guidance, some patents may uncover details on the advances.

Patent assigned to ABB Robotics Inc.(Thorne, 1997), explains the robotic control system for repositioning the EOAT to the new position with the assistance of video display showing the coordinate points of the EOAT. Work points recovered from the robot controller are displayed on the video screen for easier operator control and programming.

This allows the technician to select and designate the work points which are to be manipulated in terms of position and/or location. Once the points are saved, the program is then recorded to the robot controller. The patent demonstrates easier manual manipulation of the robot adjustment with the help of the 3D screen, however, it still requires human assistance each time robot manipulation is required.

Another ABB Robotics Inc. assigned patent (Abare et al., 2003), describes the robotic pallet welder machine used for manufacturing plastic fuel tank and adapting to different part variations. This configuration describes the linear transfer machine with multiple processing stations (i.e. boring and welding). Patent defines the system which includes 3D vision camera located on the overhead support above the fuel tank. The vision system scans the area of interest on the fuel tank during each cycle, once the palletized fuel tank enters the station. Once the scan is completed, the location and the planarity data are communicated to the robot processing the part. The patent further goes on describing the robot and machine arrangement, as well as a brief description of the sequence of operations. However, the patent does not describe the algorithm, communication protocol or any other detailed description regarding the robotic adaptability to part variations. In addition to this, this machine setup with the overhead 3D vision camera (assuming the 3D vision system is mounted on the servo linear slide), creates the constrain for the vision system scan path, as the feature of interest on the fuel tank may not be positioned directly under the camera. This would require various overhead support designs for different products, constraining the production line to the product on which the overhead support is designed to, and limiting the flexibility of the robotic production cell.

(Oxenfarth, 2007) describes a 3D vision system for position and angle readjustment of the processing unit in fuel tank applications. The patent designates two different robot arrangements. The first arrangement describes the relationship between the two robots, one of which carries 3D scanner while the second robot carries the EOAT for plastic fuel tank welding. Once the first robot would scan the area of interest, the position would be translated to the second robot with EOAT, which would adapt to the new position. This shows some similarity in the arrangement with (Abare et al., 2003), with the exception that the camera is mounted to the robot instead of the overhead frame structure. (Oxenfarth, 2007) presented the second arrangement with the 3D vision camera being mounted to the EOAT on one robot, eliminating the second robot altogether. This physical component arrangement appears to have certain similarities to this thesis research as well as patent applications (Novakovic & Holtkamp, 2017a), (Novakovic & Holtkamp, 2017b), and (Novakovic & Holtkamp, 2017c). Aside from the robot arrangement, this patent does not provide any description of the algorithm, device correlation, or communication protocol description.

(Weber, Lane, & Novakovic, 2012a) and (Weber, Lane, & Novakovic, 2012b) is another patent for fuel tank finishing/welding applications. The patent describes the tooling arrangement and operation of scanning the outside surface of the fuel tank and triangulating the position to the robot, for positioning/welding components inside the workpiece interior (i.e. fuel tank) and the method of using the same. The patent describes 3D scanning of the object exterior surface and triangulating the feature position back to the robot in order to reposition the components holder to the inside of the work piece for welding. Once the scan is performed, the robot EOAT enters the fuel tank through the sender unit (i.e. fuel pump) access opening and positions the component into alignment with the inside contact surface under the region of interest. Published material provides the information that the 3D vision camera, robot controller, and the PLC devices are used. However, the patent publication does not go into detail describing the systematic approach, algorithm, component correlation, or method on device communication/protocol.

2.3.1 Patents Literature Review

Patents review section seems to follow a very similar pattern in terms of patent information availability. The majority of the systems are used for part processing without providing enough manifestations on the systematic approach or details to understand the system structure and methodology (Risch, 2015). This is mostly as these systems are considered trade secrets (Canadian Intellectual Property Office, 2015) and manufacturers are wary of releasing any information as patents do not always provide full protection. This in return makes these systems difficult to understand or to be built by the person skilled in the art.

Although reviewed patents do not satisfy this research criterion in regards to the design detail, the objectives specified can be used for selecting an appropriate approach for the systematic detail design.

Table 2-Patent Research Gaps

		Integration						Capability				Value				Details			
		Single Robot	Multiple Robots	Single Camera	Multiple Cameras	PLC Communication	Robot Communication	Position Adjustment	Inspection	Different Outputs	Integration Ease	Production Cost Saving	Quality Increase	Material Handling	Part Processing	Task Clarification	Conceptual Design	Embodiment Design	Design Detail
Patents	ABB Robotics Inc. (Thorne, 1997)	✓					✓					✓	✓		✓	✓			
	ABB Robotics Inc. (Abare, et al, 2003)	✓	✓	✓	✓		✓	✓				✓	✓		✓	✓			
	Oxenfarth, 2007	✓	✓	✓	✓		✓	✓				✓	✓		✓	✓			
	Weber, et al (2012)	✓		✓			✓	✓				✓	✓		✓	✓			

✓	-Explored
	-Not Explored

2.4 Industrial State of the Practice

Since the introduction of vision guided robotics (VGR), the initial systems were introduced with 2D vision cameras. This arrangement allows for X, Y, R or X, Y, Z robotic adaptation depending on the camera used (Fanuc Robotics America, 2012). The introduction of 2D vision-guided robotic systems allowed for significant scrap reduction in material handling operations depending on the application. And even though 3D vision guided robotics have been introduced to the industry, many applications still remain utilized by 2D systems, forcing manufacturers to keep advancement on these systems. Applications using randomly placed objects on the same plane where the object tilt is not present are an ideal application for these systems (Anandan, 2014). These systems are fully pre-programmed with the set of tools utilized for the application (e.g. parameters, conditions, etc.). The user interface allows for easy setup and the PC-based programming tools provide a platform for easy integration (ABB, 2013). However, once the object tilt angles do become present, 3D vision guidance is required.

2.5 Industrial State of the Art

Part variety and product demand change drive the need for flexible manufacturing systems. Constant tooling change-over and the introduction of new production components requires perpetual tooling/machine adjustment until the production is stable. In order to solve this issue, many equipment manufacturers turn to readily available industrial solutions. Robotic manufacturers such as Fanuc and ABB were some of the first in the industry to introduce vision-guided robotic systems.

Fanuc iRVision consists of several platforms (Fanuc Robotics America, 2016):

- 2D Vision Guidance allows the robot to accurately position the EOAT to the part location in X, Y and R (rotation) position.
- 3DL Sensor provides the robot with the ability to position the EOAT in X,Y,Z location as well as the angle and rotation (W,P,R).
- Visual Line Tracking system is based on the 2D vision camera platform. The system provides the ability to the robot to pick and place the components to/from a moving conveyor by monitoring the encoder sensor which provides the conveyor speed and the position of the object on it.
- Vision Guided Depalletizing is another form of a system built on the 2D platform. In addition to X,Y,R direction corrections and calculations, the system will also calculate the Z height and reposition the tool center point accordingly.

Unlike Fanuc, ABB uses third part vision systems in order to provide their robots with the vision guidance (COGNEX, 2017). Companies like Cognex and Braintech provide this ability by integrating their products into the robot controllers (RobotWorx, 2016) for different uses; such as bin picking and processing applications. This approach provides ABB with similar capabilities as Fanuc (ABB, 2008).

- 2D Vision Guidance allowing robot to accurately position the EOAT to the part location in X, Y and R (rotation) position.
- Single camera information in 4 degrees of freedom (X,Y,Z,R)
- Single camera 3D technology for full 6 degrees of freedom adjustment (X,Y,Z,W,P,R)
- Surround 3D imaging combining information from multiple cameras viewing parts from different angles

2.6 Summary

Literature review presented in this chapter summarizes academic, patents, state-of-the-practice and state-of-the-art solutions regarding vision-guided robotic applications for the part to part variation handling. As creative and efficient academic solutions may be, they do not present a feasible solution to the industrial requirements, mostly due to the level of complexity and lack of industrial devices use. Patents, on the other hand, do not disclose enough information on the system design or detail to understand the structure or the function. State-of-the-practice and state-of-the-art provide already well-developed solutions but do not disclose any information in regards to system design. Rather, they provide an out-of-the-box solution for the integrators. Therefore, the research and results presented in the following chapters address this lack of information and knowledge.

CHAPTER 3: DESIGN OF AN ADAPTABLE TOOLING SYSTEM FOR PART TO PART VARIATION PROCESSING

3.1 Systematic Design Process

The primary objective of this research thesis is to design a system that would automatically adapt to part variations commonly found in the plastic manufacturing industry. Planning a system design where different components are assembled in order to provide this objective brings uncertainties which need to be addressed prior to components integration. In order to achieve this design, extensively used IDEF0 as well as systematic design approach by (Pahl, Beitz, Feldhusen, & Grote, 2007) was chosen in order to select, configure, and integrate components into the system, by observing and eliminating the constrains each component might carry.

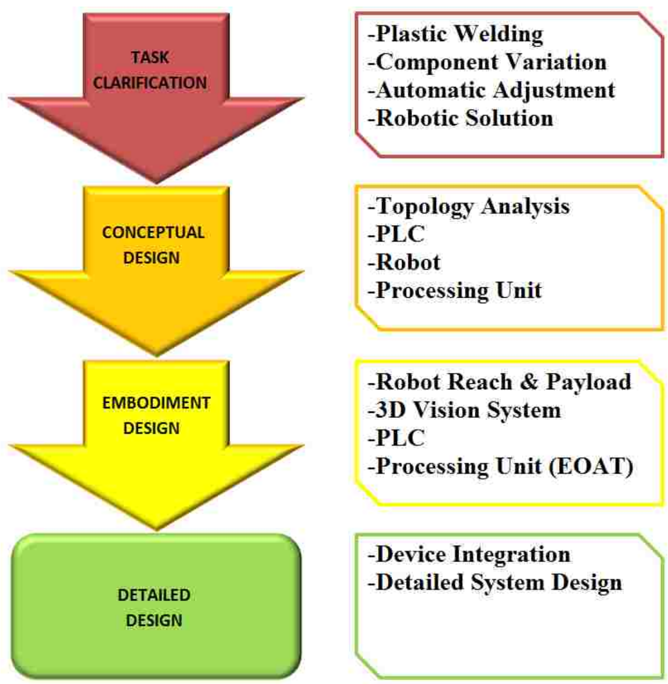


Figure 15-Systematic Design Methodology

3.1.1 Task Clarification

The fundamental problem in many blow moulded components processing is the part variation. This variation leads to major automotive recalls which more often than not, create large volumes of fuel tanks which needed replacing in the past (Grande, 2011), (ARFC, 2002) and are still occurring (Mazda, 2016b), (Honda, 2016), (Mazda, 2016a). Part to part variations typically found within mass produced plastics parts requires periodic machine adjustment by maintenance technicians. This in return generates production downtime, extra production cost, increases scrap rate and lowers overall equipment effectiveness (OEE).

In order to eliminate this issue, adaptable tooling system is required so the feature on the fuel tank and component being welded can be matched correctly. Readily available industrial components such as robots, PLCs, cameras, etc., will only be used for the system design.

Process cycle time should be lower than compared to current production as the ideal condition would always be achieved, and the need for the matching time to conform the fuel tank surface to the hot plate is decreased.

The system should allow for easy integration into existing robotic production without major equipment changes. The addition of the system components (i.e. camera) to the current production system should be performed with ease, assuming that the current production already utilizes industrial robots and PLC.

Once integrated, the robot should automatically adjust the EOAT to the new position on the fuel tank where the feature of interest is deviated. Thus, resulting in adaptability to part variations.

3.1.2 Conceptual Design

In order for the system to reposition the processing unit to the new feature location, it is essential that the system is capable of adjusting in X, Y, Z, W, P, R directions. Thus, 6 degrees of freedom (6 DoF) robot will be used in order to provide the flexibility in position adjustment and orientation. In addition to the robot, other components listed below will need to be used in order to administer the position change.

- 3D vision system will be used for topology generation.
- PLC will be used to provide communication between the network devices and to perform process making decisions.
- Processing unit will be used as robot EOAT for fuel tank welding.

Robot required for the application should have the ability to adjust in 6 degrees of freedom; therefore, an articulated 6 DoF robot is required. For this application, an existing Fanuc R2000-iB/165F robot will be utilized. Since Fanuc robots are most commonly found in the worldwide manufacturing settings (Christensen, 2016), Fanuc TP robot programming language is well developed for most operations regarding the robot movement and position.

Having the camera mounted as part of the EOAT, two user tools will be assigned to the robot; one for the camera and second for the processing unit. With this approach, the robot can provide direction and velocity, producing an accurate and repeatable camera scan start location, which will be used for analyzing the object topology. This procedure is achieved by moving the robot over top of the object and scanning the surface on the initial component. Once this is performed, the camera will record the feature position (i.e. hole) in terms of X, Y, Z, W, P, R location, while simultaneously robot user tool position is recorded to the same physical feature of interest (i.e. fuel tank hole) location. This procedure creates a correlation between the feature of interest on the camera image and the robot EOAT position register (PR). This position will be assigned as the "master" point from which all subsequent feature locations will be measured. Once position difference on the next component scan is calculated by the camera, the variation in position will be sent to the PLC where it will be checked and then transferred to the robot. The robot will initially move EOAT to the "master" position, and then perform the difference in location regarding X, Y, Z, followed by W, P, R directions. Once process (i.e. welding) is completed, the subsequent component can be processed.

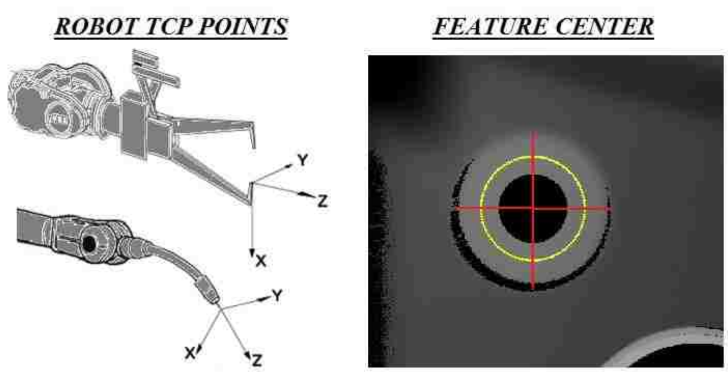


Figure 16-Tool Center Point (TCP) Synchronization

3D vision system will utilize manufacturer's software and tools in order to find features in 3D space (SICK, 2013). Once feature location and position in 3D space is recorded, it is referenced to the image upper left-hand corner (origin point). It is essential to mention that this image corner is located on the image start scan line. Thus, moving the scan start location without repositioning the object will change the feature location on the image. Therefore, it is critical to assure that the image scan location is repeatable and accurate.

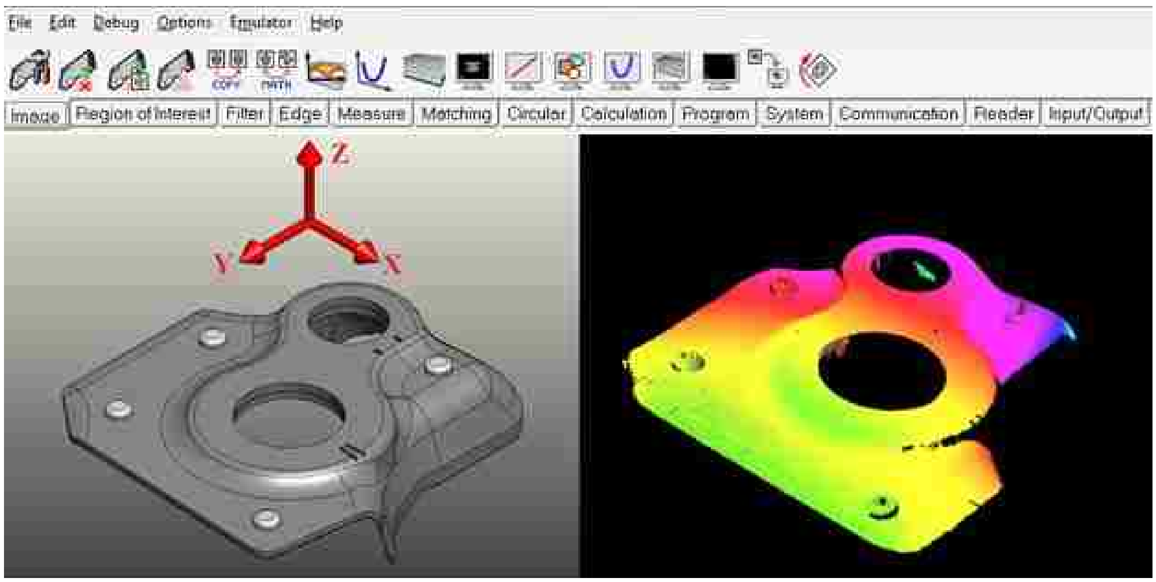


Figure 17-3D CAD and 3D Scanned Image

Once the first image ("master") is scanned, the position of the feature will be marked as [0,0,0,0,0,0] (meaning that the "position offsets" are not present), from which all other position will be measured. Once calculated, all changes in position will be sent to the PLC.

Siemens Step 7 PLC system will utilize a Ladder logic programming, typically found in the manufacturing plants throughout North America (Smith, 2003). This type of programming consists of a similar structure found in the relay logic for electrical wiring control circuits.

Part of a PLC referred to as Function Block Diagrams (FBD) will be utilized for describing the function between the input and output variables.

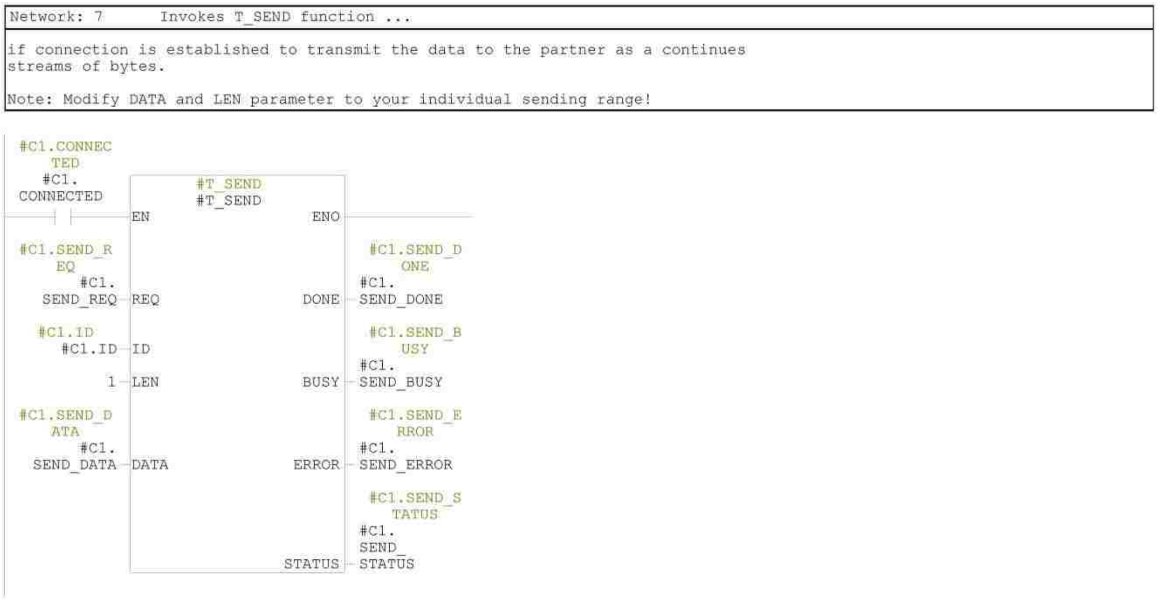


Figure 18-PLC Program Example

However, due to PLC inability to send or receive decimal values to and from other network devices, position locations will be required to be converted into integers prior to any communication.

<u>*EOAT*</u> will utilize a standard processing unit (i.e. Fusion Unit). Unit consist of the following assemblies:

- Tank Hot Plate: used for fuel tank melting
- Part Hot Plate: used for melting the component being attached to the fuel tank
- Holding Fixture: used for holding the component being attached to the fuel tank

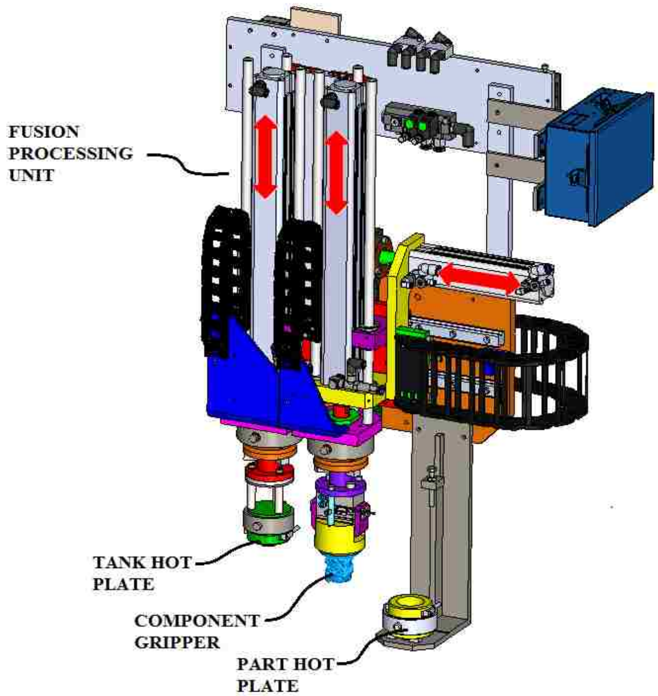


Figure 19-Fusion Unit Design (Courtesy SPM Automation (Canada) Inc.)

Robot TCP is recorded at the extension of "Component Gripper" cylinder 20 mm prior to the end of cylinder stroke (380 mm from the position shown in Figure 19).

The conceptual sequence of operations is outlined in Figure 20 below.

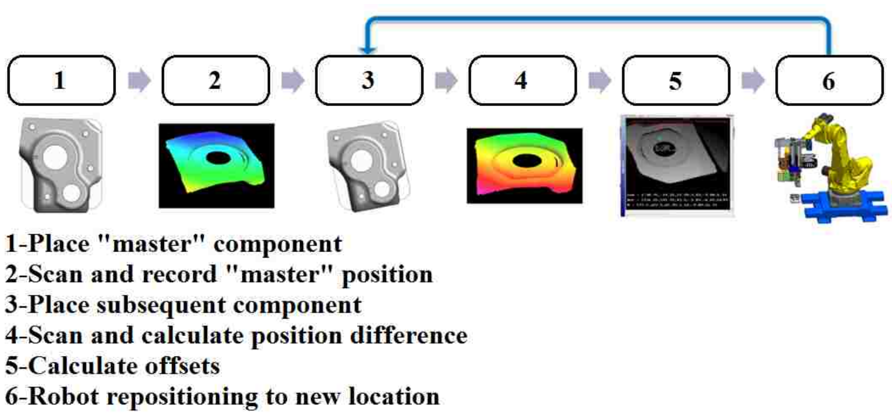


Figure 20-System Concept © 2017 IEEE

The scope of each component is outlined in Figure 21 below.

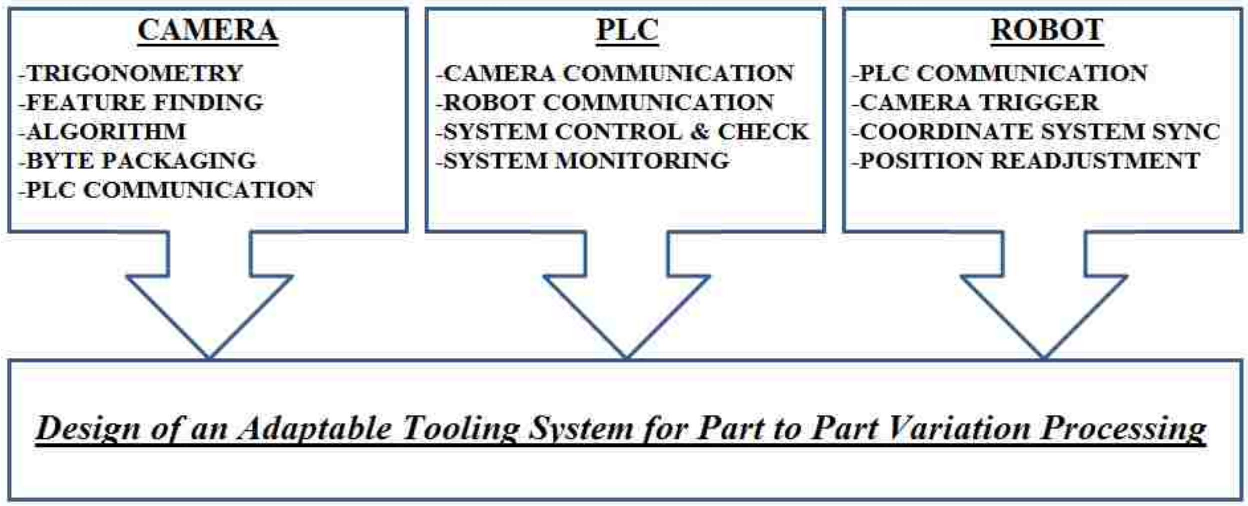


Figure 21-Component Scope © 2017 IEEE

Estimated cost of $40,000 is used as a benchmark, considering the cost of the 3D vision system purchase ($15,000) along with the cost of programming and integration to the existing robotic cell.

In addition to the cost of the system integration, tolerance needs to be considered. At this point in the conceptual design stage, repeatability of the robot needs to be added to the accuracy of the vision system. Fanuc Robotics specifies positional repeatability of ±0.2 mm (Fanuc Robotics America, 2009). However, repeatability of ±0.1 mm is possible by using special software upgrade. SICK AG does not provide the tolerance specifications in regards to the camera but rather uses an approach of applying various filter tools to enhance the image and decrease the tolerance. By analyzing the components in order to determine the possible system tolerance, pixel sizes in terms of 0.25 mm x 0.25 mm have been identified in the 3D vision. Suggesting worst case scenario where the centroid of the object may be positioned close to the corner between 4 pixels, and the system automatically applying it to one of the four quadrants, the following figure illustrates this accuracy.

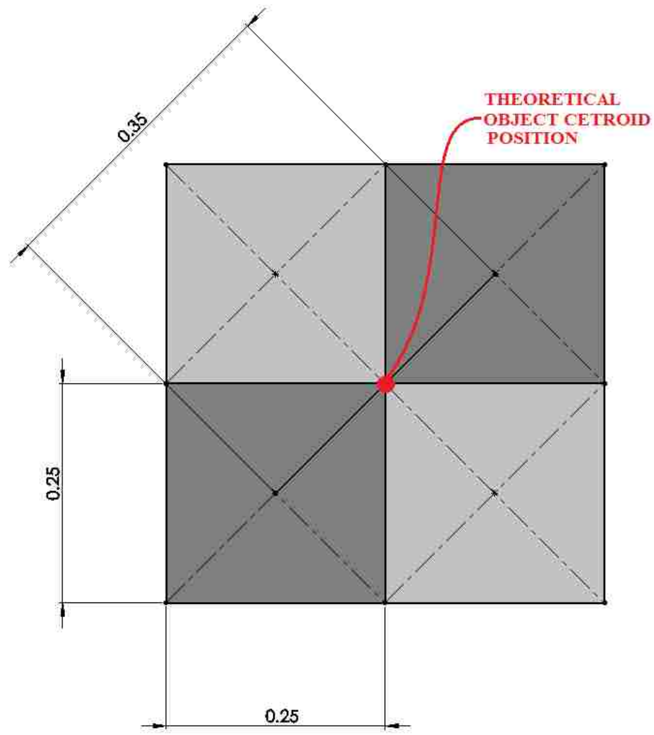


Figure 22-Worst Case Object Positioning by SICK AG Vision System

Considering robot repeatability of ±0.2 mm, an assumption can be made that the next scan start position may vary by this tolerance, thus causing the scanned object in the image to look as it has moved. Figure 22 illustrates a theoretical object centroid position in proximity of 4 quadrants, which would automatically fall within the one it is located in. However, due to robot repeatability, this centroid position may move to a different quadrant, thus generating the camera repeatability of ±0.175 mm. In order to calculate the system tolerance, both components (i.e. camera and robot) need to be added together. By doing so, theoretical system repeatability of ±0.375 mm is provided. Using this initial theoretical tolerance for adjusting the EOAT to the fuel tank, and fuel tank feature which can vary ±25.0 mm, this tolerance of ±0.375 mm provides satisfactory tolerance limit in order to pursue the research. More details on robot accuracy and repeatability are covered in section 5.1.

PLC tolerance is not included in this calculation as this device transfers the same values from the vision system to the robot; therefore, it is assumed that no error is created during this information transfer.

The conceptual design stage is concluded with the use of 6 DoF robot, 3D vision system, PLC, the processing unit, and creating the correlation between these devices. Combining the components together will provide the system structure. This arrangement will provide flexibility for position adjustment, allow for information exchange, and the ability to process the parts in a production environment.

3.1.3 Embodiment Design

Embodiment design phase represents a working structure of the project, which will develop the construction structure of each component and their purpose.

3.1.3.1 Camera Embodiment Design

Having the camera as part of the EOAT, accurate robot speed is calculated by using predetermined image length and the image profile size by using the equations below:

$$No.of\ Objects\ Scanned/sec = \frac{Robot\ Speed}{\text{Image Length}} \tag{1}$$

$$No.of\ Profiles\ to\ Capture\ an\ Object = \frac{Profile\ Rate}{No.of\ Objects\ Scanned/sec} \tag{2}$$

$$Profile\ Distance = \frac{Image\ Length}{No.of\ Profiles\ to\ Capture\ an\ Object} \tag{3}$$

Signal to activate the camera scan is sent through the End Effector (EE) connector on robot's axis#2 once the position is reached. During this motion, camera velocity is attained, as constant scan speed is required to provide an accurate image. Activating the camera scan during acceleration or deceleration of the robot will create "stretched" or "compressed" image, providing incorrect feature position values during the calculations.

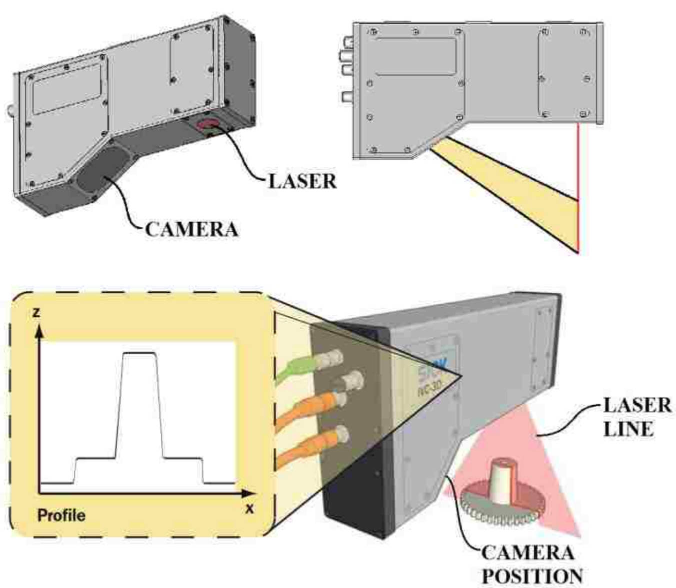


Figure 23-3D Vision Image Scan (Adopted from SICK, 2013)

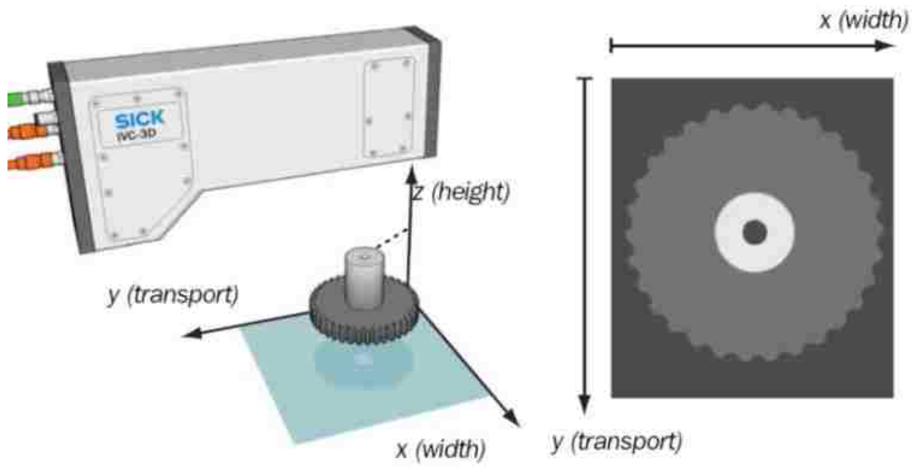


Figure 24-3D Vision Scan Generation (Adopted from SICK, 2013)

During the image scan, PLC byte is sent to the camera. This byte identifies the program step to be executed. Depending on the program structure, a byte may identify the program step or action. As the topology is generated, programming tools are used to identify the area of the image to be analyzed.

By using SICK IVC-3D software, an array of the tools is presented for object evaluation as shown in Figure 25.

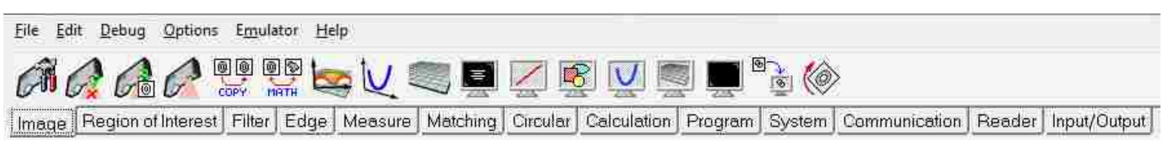


Figure 25-IVC Studio Tools

Region of Interest (ROI) Tool: Used to identify the area in the image for analyzing.

Blob Finder Tool: Used for feature analyzing once the feature is identified by the Region of Interest (ROI) step. This step also provides the X, Y centroid location as well as the feature size. It can also be used to provides the limit values used to set the restrictions in part variation size (i.e. hole diameter).

Fit Surface Tool: Used to define a plane which can be used for attaining the Z location of the feature as well as minor plane angles.

At this point, the system is able to determine X,Y,Z points and minor angles of the feature. Once computed, the values can be converted to integers and sent to the PLC.

3.1.3.2 PLC Embodiment Design

In addition to the position integer values, different information is also transferred to the PLC in order to assure that the scan data is correct. Values defining new image scan, fault code, program step, offset limits, etc. are presented and then analyzed by the PLC. If the values received are within specified limits set in the program, the data is then transmitted to the robot and the process is allowed to continue.

3.1.3.3 Robot Embodiment Design

Once the image is recorded, the topology is analyzed by the camera and the feature coordinates are sent to the PLC. During the new position calculation by the camera, robot initially moves to the "master" position (recorded by position register), from where the new offset position will be determined by the information sent by the PLC. This information is stored in the robot registers and calculated based on the information received by group input/outputs. Initially received and stored as integers, the information is converted into decimal values prior to adjusting to the new position.

Robot Group Inputs (GI) are organized as per below:

GI[n]=Integer for X before decimal place (4)

GI[n+1]=Integer for X after decimal place (5)

………

Robot Registers are normally used to store numbers which can be used for arithmetic operations, cycle counts, track part counts, etc. (Fanuc Robotics America, 2003). Thus, these registers will be used to store the values from the PLC, once converted into decimal values per guideline below.

R[n] (X linear offset value) (6)

R[n+1] (Y linear offset value) (7)

………

Methodology and the equations of converting GI [n] and GI [n+1] as X position decimal offset value from integer is presented below:

Extracting integers into a value before decimal place:

R[n]=GI[n]-128 (8)

Extracting integers into value after decimal place:

R[X:SCRATCH PAD]=GI[n+1]-128 (9)

R[X:SCRATCH PAD]=R[X:SCRATCH PAD]/100 (10)

Adding value before and after decimal together:

R[n]=R[n] + R[X:SCRATCH PAD] (11)

Once the information is extracted, the values are stored in the robot registers.

Position registers (PR) are used to store the positional information (X,Y,Z,W,P,R configuration). Fanuc robotics provide up to 200 position registers in the controller (Fanuc Robotics America, 2003), which are identified by the numbers. Therefore, “master” position PR[X] is used by the case study as the position correlated to the feature center at the master location from which all other offsets will take place. Two more position registers are used for major and minor axis offsets. New position register for all major axis offsets is assigned to PR[X+1], while minor axis offsets are provided by PR[X+2].

Initially, all offsets will need to take place in the world followed by the angular adjustments:

PR[X+1, 1]=PR[X,1] + R[n] (12)

PR[X+1, 2]=PR[X,2] + R[n+1] (13)

PR[X+1, 3]=PR[X,3] + R[n+2] (14)

PR[X+1,4]=PR[X,4] (15)

PR[X+1,5]=PR[X,5] (16)

PR[X+1,6]=PR[X,6] (17)

This is followed by the angular adjustment:

PR[X+2,4:SCAN TOOL ANG]=R[x+3] (18)

PR[X+2,5:SCAN TOOL ANG]=R[n+4] (19)

PR[X+2,6:SCAN TOOL ANG]=R[n+5] (20)

In this stage of the systematic design, the design of each component is created in accordance with technical principles. By completing the embodiment design stage, a definitive layout is created.

3.1.4 Detailed Design

In the previous Design Embodiment phase, following is presented:

- Camera programming and object correlation to robot in 3D space
- PLC communication, byte information, and information transfer between devices
- Robot programming, position offsets, and correlation to the image

At the end of each scan cycle, the feature location along with measured and offset values is displayed on the HMI screen for reference as shown in Figure 27. By using the "Communication" (C) values displayed on the HMI, robot offsets can be checked by matching the same values on the group input (GI) side of the robot controller. Same values can also be used for monitoring part to part variation during the manufacturing process.

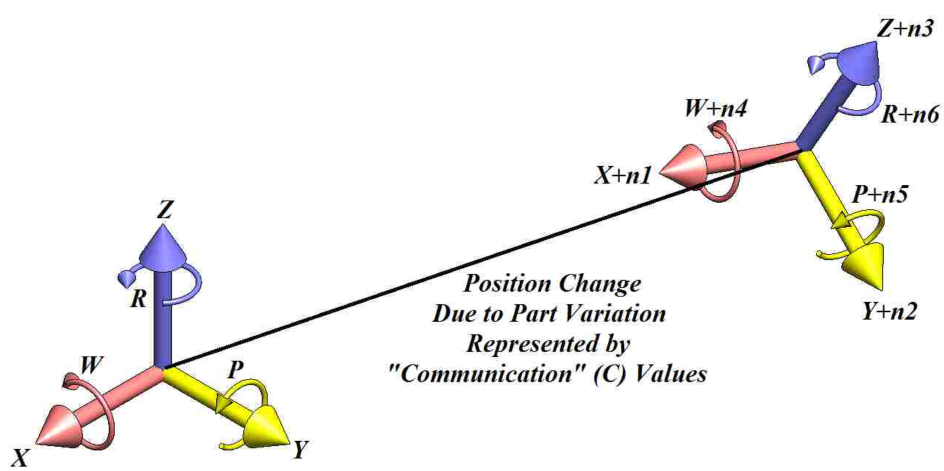


Figure 26-Robot Position Change

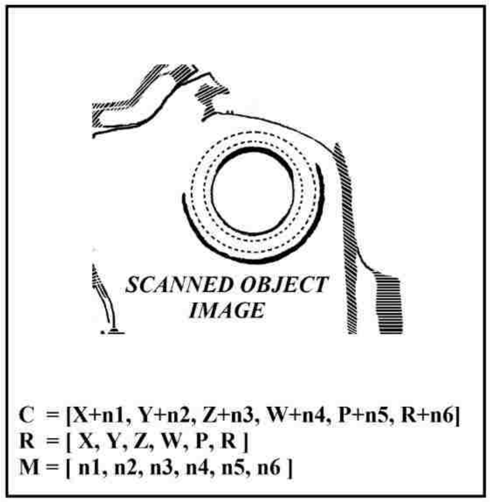


Figure 27-HMI Position Adjustment Display

Representation of "C", "R", and "M" values in Figure 27:

- *C* - Communication offsets values robot needs to offset from the "master" position
- *R* - Reference values representing the "master" position (robot PR[X]) from where every subsequent feature position is measured
- *M* - Measured values representing the feature location in the image

It is important to mention that during the machine design singularity occurrence can be avoided by utilizing Fanuc Roboguide software (Schollenberger, 2015), or by using 3D CAD model and assuring that no two robot joints would line up making them redundant. Any potential singularity occurrence can be avoided by manipulating robot position relative to the object being processed. Figure 28 shows the reachable robot workspace (Spong & Vidyasagar, 2008) relative to the fuel tank, and the real-estate available for robot repositioning in a case of singularity.

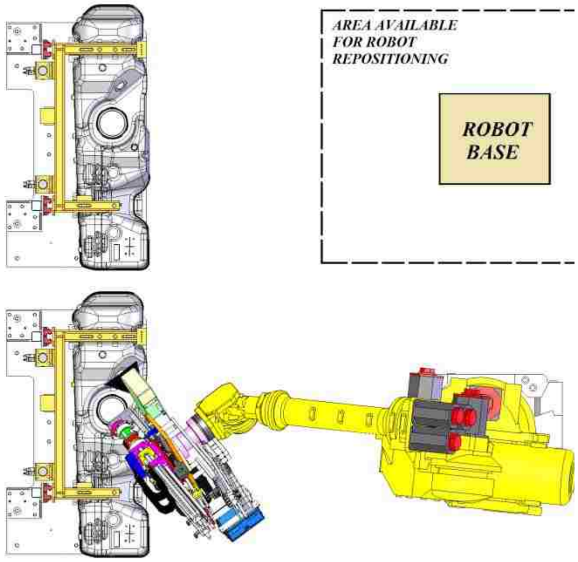


Figure 28-Robot Position Relative to Fuel Tank (Courtesy SPM Automation (Canada) Inc.)

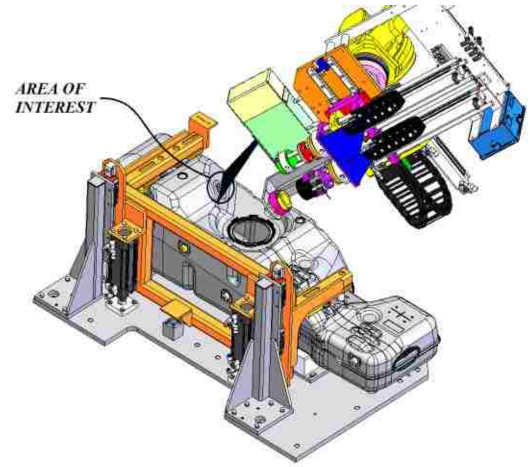


Figure 29-Fuel Tank Feature Scan Area (Courtesy SPM Automation (Canada) Inc.)

Within this work space, fuel tank fixture design is required to allow for scan path clearance of the feature as shown in Figure 29.

Singularity for this research was checked by utilizing 3D CAD model provided by SPM Automation Inc. Designing all components for the research in 3D CAD prior to any manufacturing and/or testing, the position of robot joints in 3D CAD did not show any possibility for singularity occurrence. The same method was used to check for robot reach and joint limits.

Another constrain on the 3D vision system is direct sunlight on the object being processed. This represents a common problem with machine vision, as it affects the image geometry by creating noise on the image (Microscan, 2013). System Limitations section provides more insight on this problem as well as the resolution.

Completing the final stage of the systematic design, the design of each component is finalized and potential complications are addressed. The system is provided with enough information to lead to production build and programming.

3.2 IDEF0 Design Process

IDEF0 is a structured modeling method used to develop a functional or activity model of an enterprise by describing what is done without regards to the sequence (W. ElMaraghy, 2015). It is used to graphically display any operation through building blocks as shown in Figure 30. The process starts with scope definition by identifying the main function of the model. Once the main function is determined, lower levels diagrams can be generated.

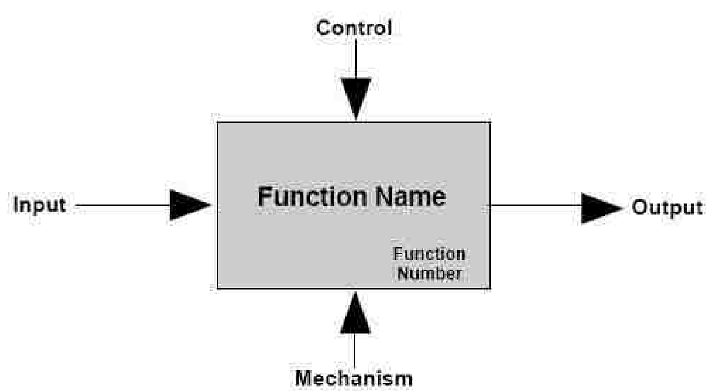


Figure 30-IDEF0 Representation (Source: Wikipedia, Image by Defense Acquisition University)

Diagram order for this experiment is defined as following:

- A_0- Design of an Adaptable Tooling System for Part to Part Variation Processing (Figure 31)
- A0-Decoupled Node of the Design of an Adaptable Tooling System for Part to Part Variation Processing (Figure 32)

- A1-Task Clarification Phase (Figure 33)
- A2-Conceptual Design Phase (Figure 34)
- A3-Embodiment Design Phase (Figure 35)
- A4-Detailed Design Phase (Figure 36)

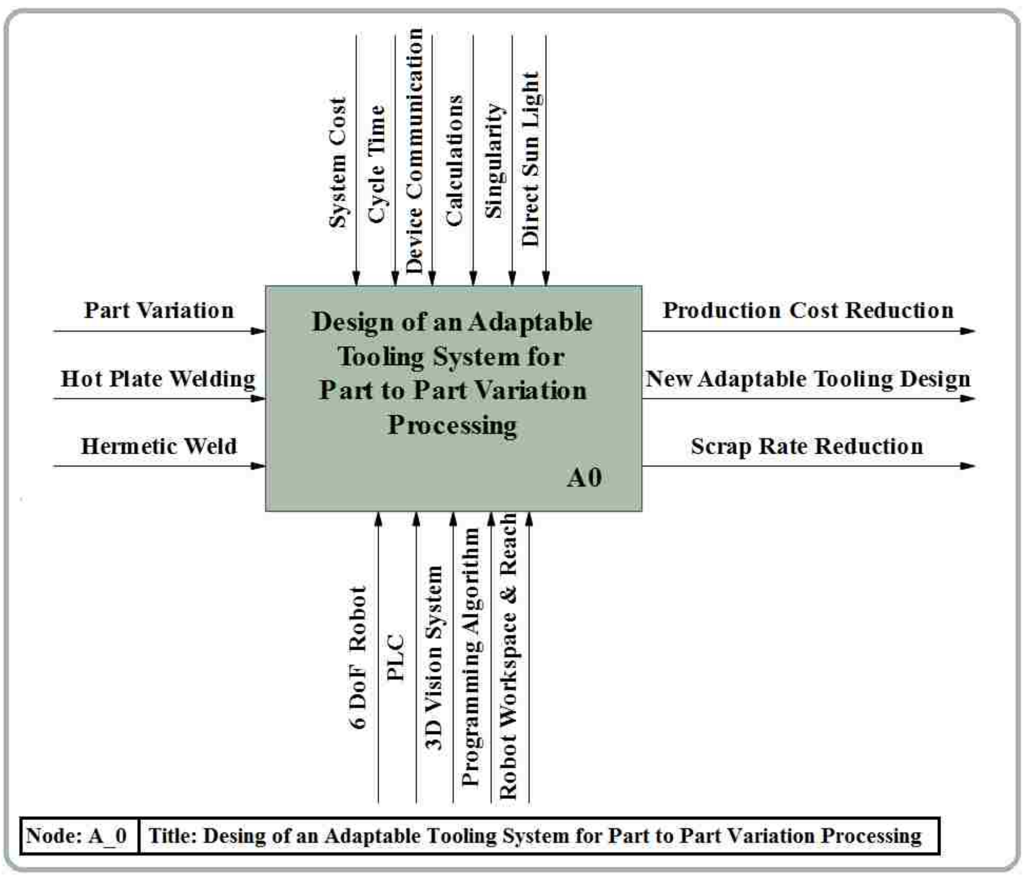


Figure 31-Main Function Block

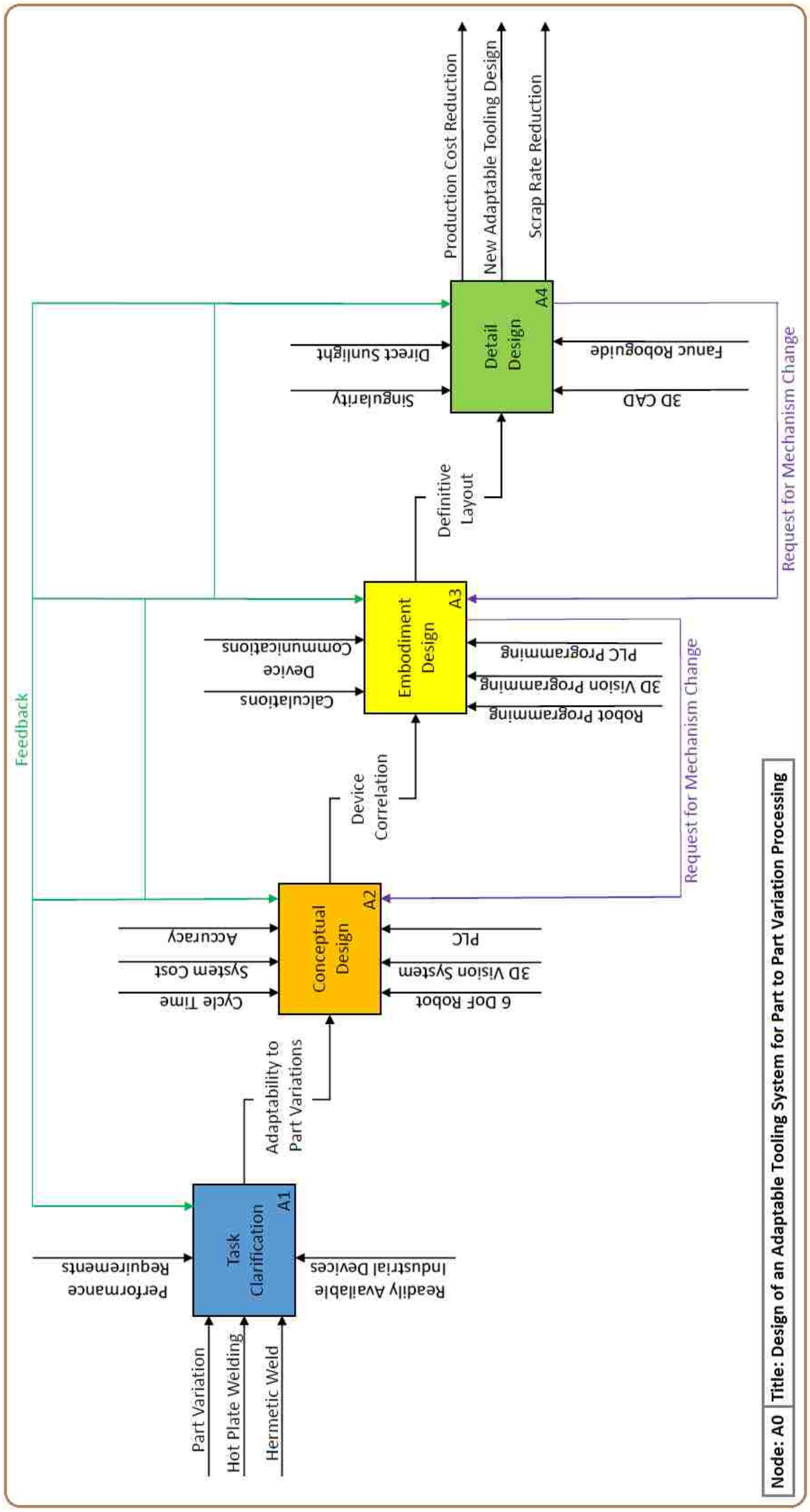


Figure 32-Decoupled Node A0

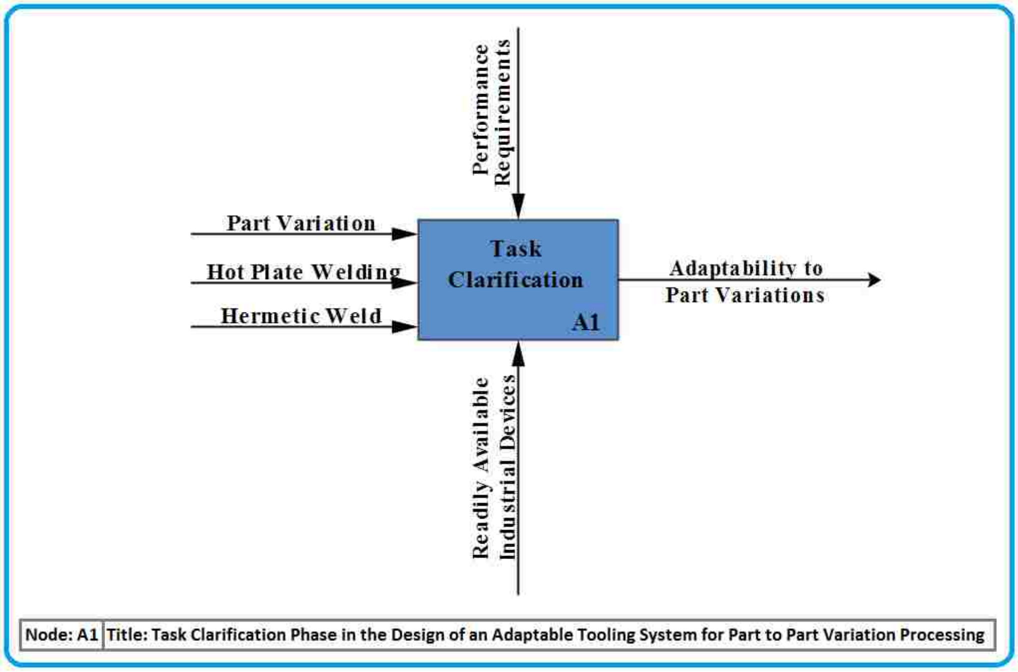


Figure 33-Node A1 (Task Clarification Phase)

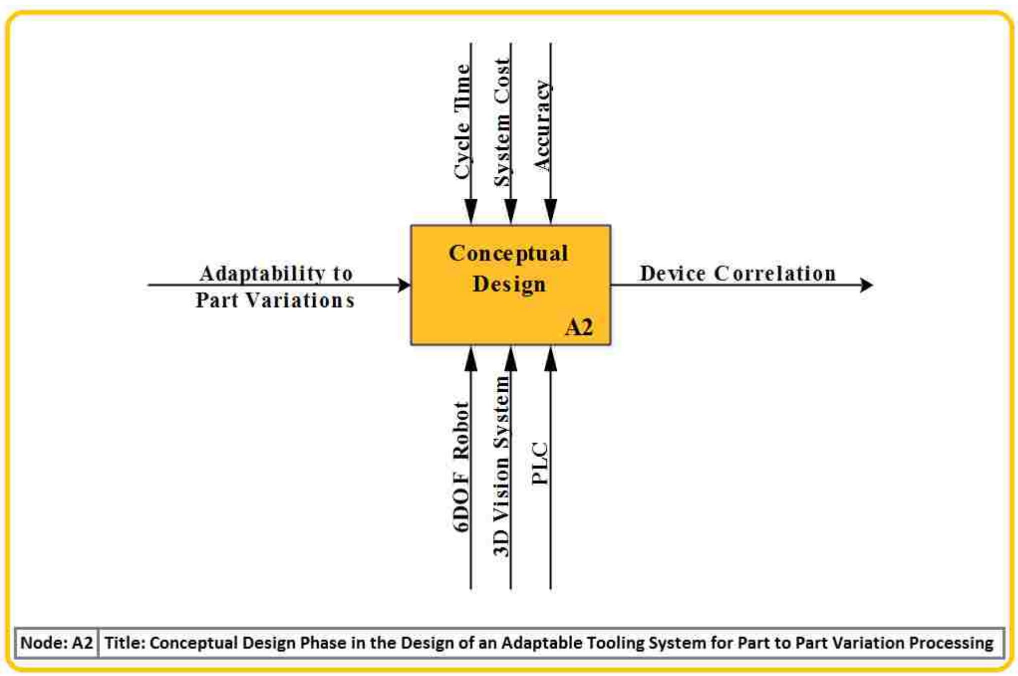


Figure 34-Node A2 (Conceptual Design Phase)

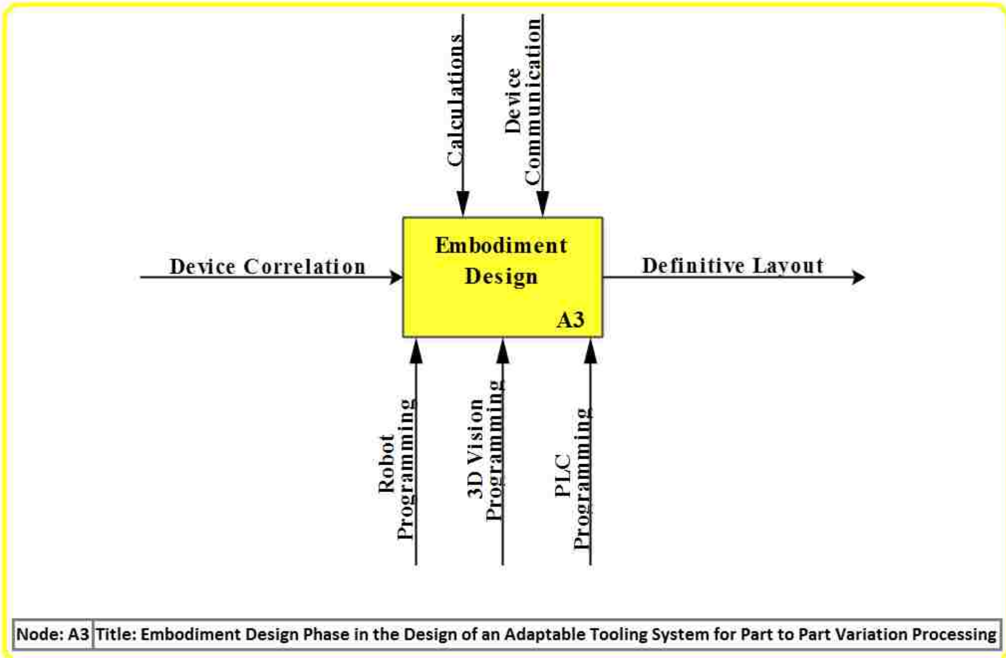


Figure 35-Node A3 (Embodiment Design Phase)

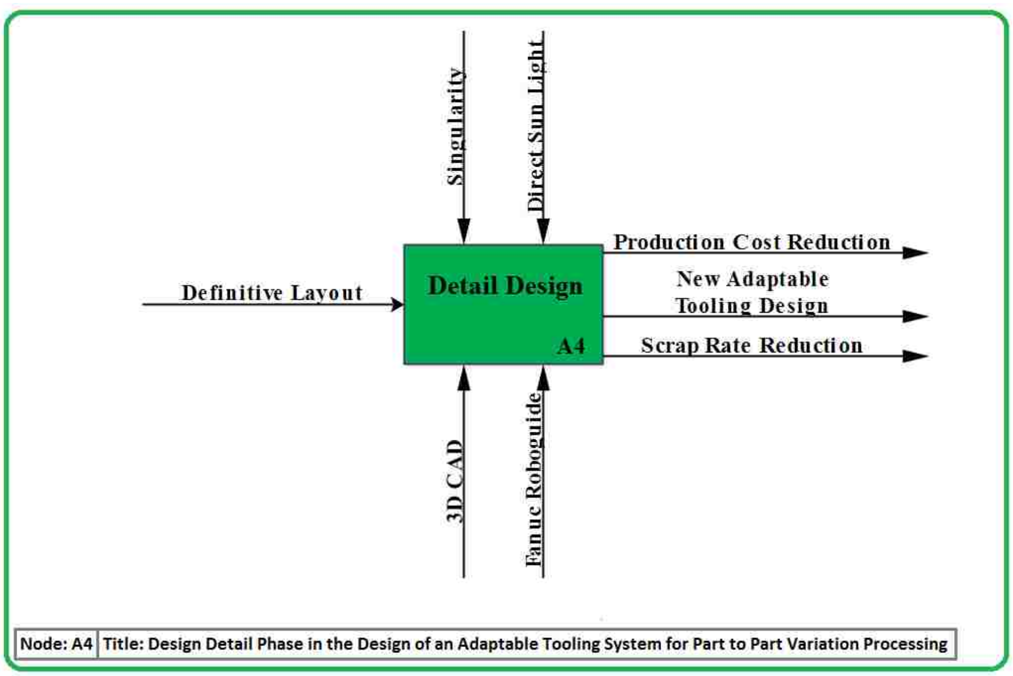


Figure 36-Node A4 (Detailed Design Phase)

CHAPTER 4: IMPLEMENTATION CASE STUDY

4.1 Test Equipment

The primary goal of this research thesis is to accurately design and build the system capable of adapting to different part variants. In order to provide insight on the system design and build, this section will provide the information on equipment access, and explain the case study execution.

Access to equipment is provided by SPM Automation (Canada) Inc., located in Windsor, ON. SPM Automation is a Tier 1 equipment supplier specializing in industrial automation and plastic welding applications. Full access to the prototype equipment which includes PLC, HMI, Fanuc industrial robot, vision system, processing units, etc. was at the disposal for design, development, and testing for this thesis research.

The basic equipment specifications are listed in the tables below.

Table 3-Robot Specifications

Manufacturer	Fanuc Robotics Inc.
Robot Type	R2000-iB 165F
Controller	R-30IA
Year	September 2009
Robot ID	F-87882

Figure 37-Test Robot-Fanuc R2000 iB 165F

Table 4-PLC Specifications

Manufacturer	Siemens
PLC Type	S7-300

Figure 38-Test PLC-Siemens S7

Table 5-3D Vision System Specifications

Manufacturer	SICK AG
Type	IVC-3D51111

Figure 39-Test Camera-SICK IVC-3D

Table 6-HMI Specifications

Manufacturer	Siemens
Type	IPC577C

Figure 40-Test HMI-Siemens

4.2 Test Environment

SPM Automation Inc. provided an ideal manufacturing setting for the test, by using real manufacturing equipment as well as the surrounding, where different lighting conditions equivalent to those in the production plants are provided. Figure 41 shows the prototype cell.

Figure 41-SPM Automation Prototype Cell

Figure 42-Fuel Tank Section

By using smaller fuel tank section specimen, object manipulation was easier to achieve than by using an actual full-size fuel tank. The specimen was placed on the table top located in front of the robot during the testing. Because of the specimen size, position variation was easily provided simply by moving the specimen in X, Y and Z directions. By placing the wedge under one side of the specimen, minor axis variation was achieved regarding W, P, and R angles. Figure below illustrates the different part position variations.

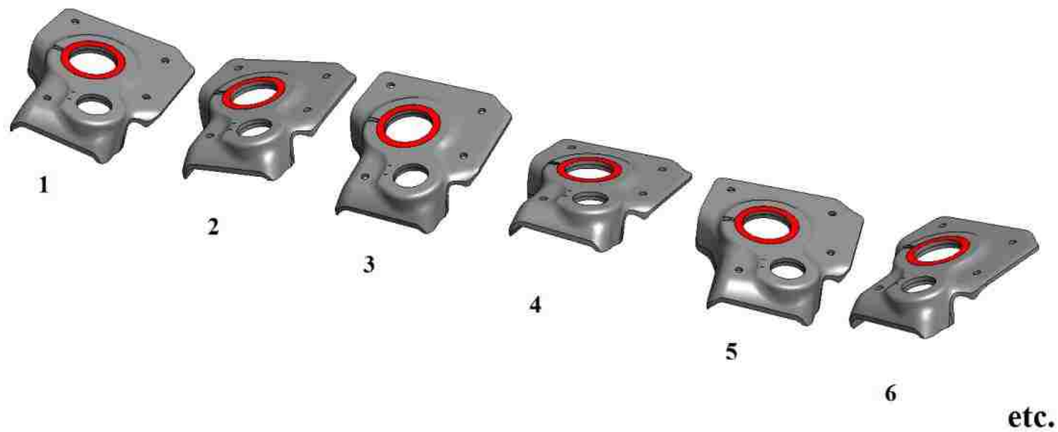


Figure 43-3D CAD Illustration of Position Variations

4.3 Hardware Integration

Existing prototype cell is provided with already existing PLC, 6 DoF robot, HMI, and EOAT. These devices are integrated together in order to provide support for small production run batches or prototype testing.

The addition of the 3D vision system required fastening the unit to the EOAT by use of mechanical brackets. Ethernet cable for PLC communication was combined with the existing robot dressing, from the 3D vision system and terminated in the electrical cabinet. Small junction box was mounted to the Fusion Unit (EOAT) to be used for electrical terminals and relays to control the camera function.

4.4 Device Communication

Device communication is established by using Ethernet IP with the following device addresses:

Table 7-Device IP Addresses

PLC:	192.198.1.22
HMI:	192.168.1.12
3D Vision System:	192.168.1.2
Robot:	N/A

All existing devices use Profibus communication (Wikipedia, 2017) for communication.

4.5 Test Procedure

This section specifies the test procedure and cycle sequence used to check the system for functionality and record the data.

Before cycle start, certain criteria was required to be checked and/or established:

- Communication check between devices
- Robot speed through object scan path set at 250 mm/sec
- Scan area defined

4.5.1 Robot

Robot path is determined initially by setting the camera scan distance to the object. The 3D vision system is manually activated through software (triggering the camera laser) while the robot with the camera is positioned above the object. Scan distance can be set by changing the robot height which moves the 3D vision system up/down, or manually through software if distance limitation allows. This procedure is performed until the object is displayed in the object window as shown in the figure below.

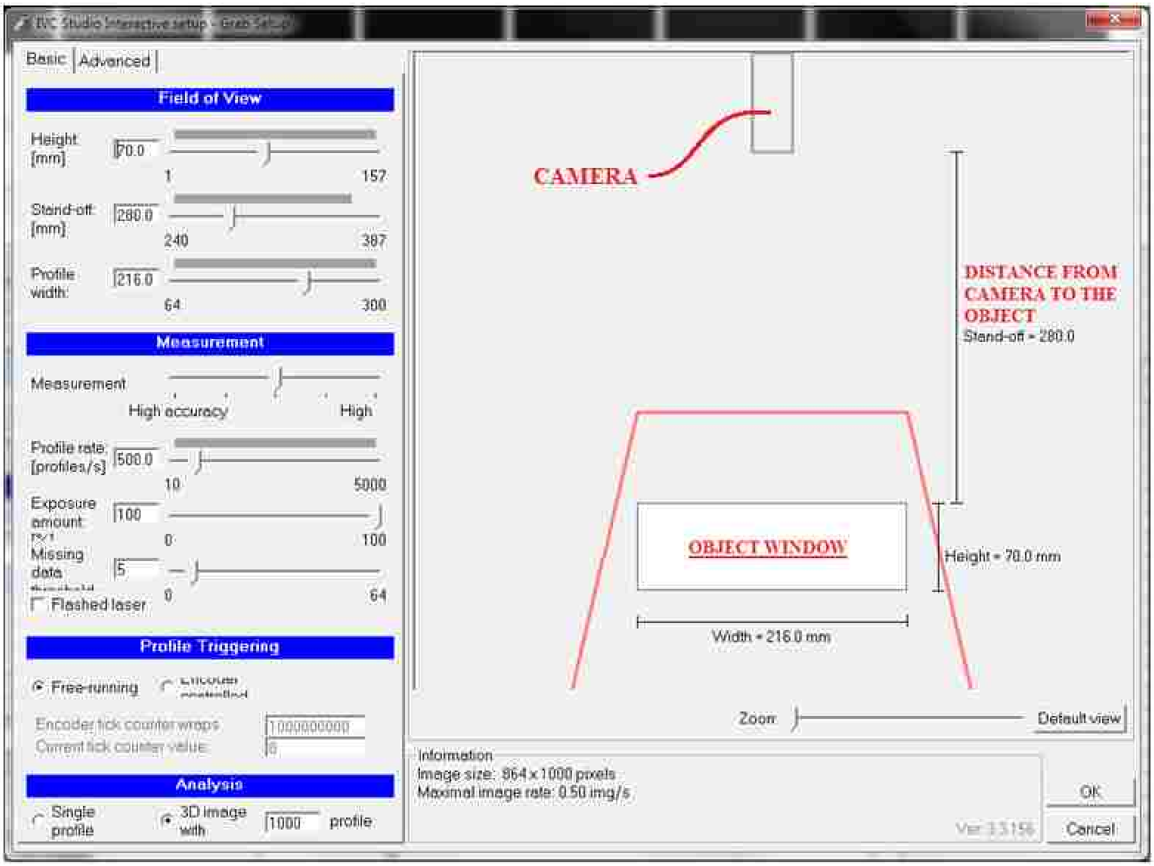


Figure 44-3D Vision System Distance Setup

Once the vision system height to the object is determined, scan triggering can be established. By moving the robot over the object at previously set height, encoder position is monitored and I/O signal from the robot is used to send the camera signal to activate the scan. By changing the robot register value for the camera scan start position in the robot program, scan start location can be moved to a different position along the scan path to start sooner or later depending on the object location. By changing the number of profiles in the camera setup screen (Figure 44), image length can be increased or decreased, thus changing the scan window.

Control relay (2823CR) used to trigger the camera scan is controlled by the robot output RO[04] through the end effector (EE) connector on robot joint#2. By supplying 24V to the relay which is terminated at camera power connection#1, camera scan is activated. Junction box with control relay is located on the robot EOAT. More information on the control wiring is detailed in Appendix A.

Figure 45-Robot EE Connector

Figure 46-Electrical Junction Box

Camera communication to the PLC is established through the Ethernet Switch. This device uses pocket switching in order to establish the communication between different devices identified by their own IP addresses (Wikipedia, 2016b). Camera IP address in this case is identified as 192.168.1.2 with subnet address 255.255.0.0.

Robot program is created by using Fanuc TP programming language called Karel, which is derived from Pascal (Robotics, 2016). Robot program is shown in the figures below.

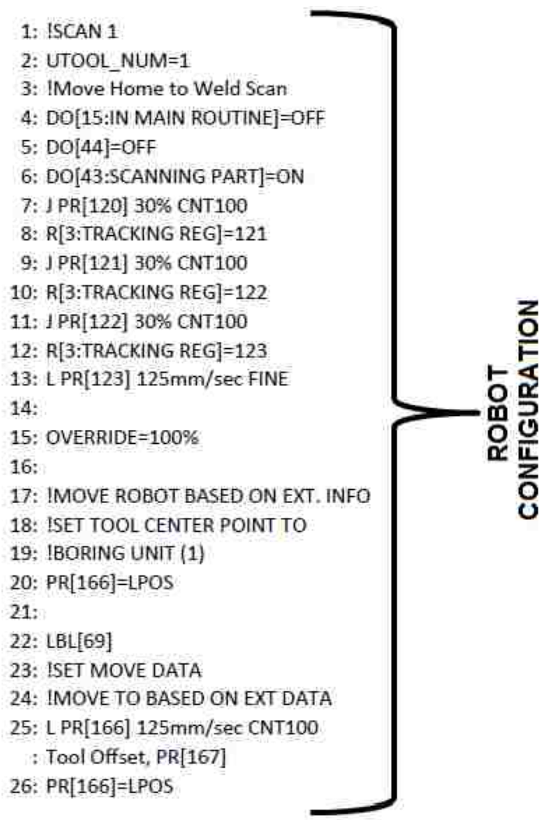


Figure 47-Robot Configuration Program Section

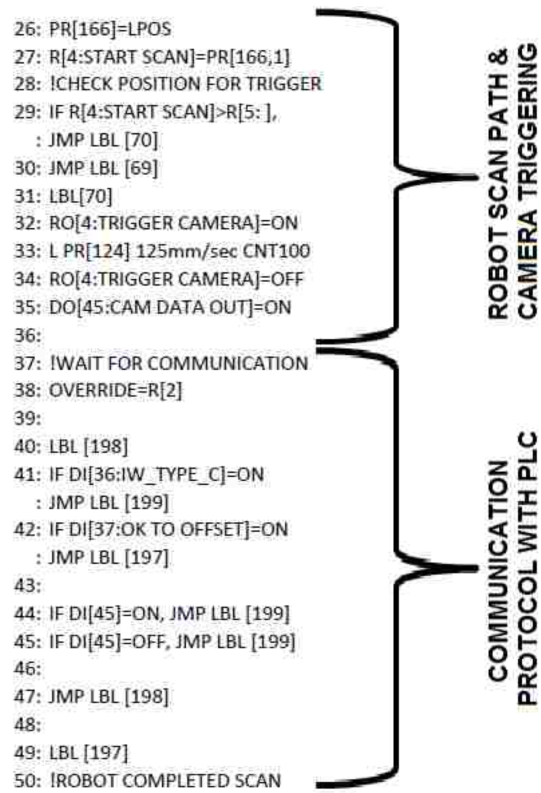


Figure 48-Robot Path and Communication Protocol Program Section

Figure 47 outlines the first part of the robot program which deals with robot configuration regarding the routine, register tracking, approach speed and type (linear vs joint robot move), and defines scan start position. The following Figure 48 describes the portion of the robot program which defines robot approach to the object being scanned as well as the communication with the PLC device. Once this programming step is finalized, the robot waits for the camera to transfer the new position coordinates through the PLC device.

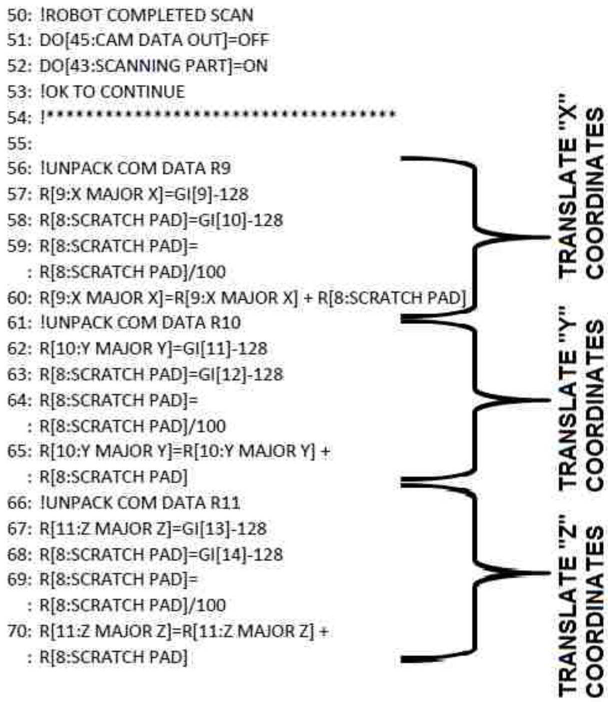


Figure 49-Robot Major Axis Translations

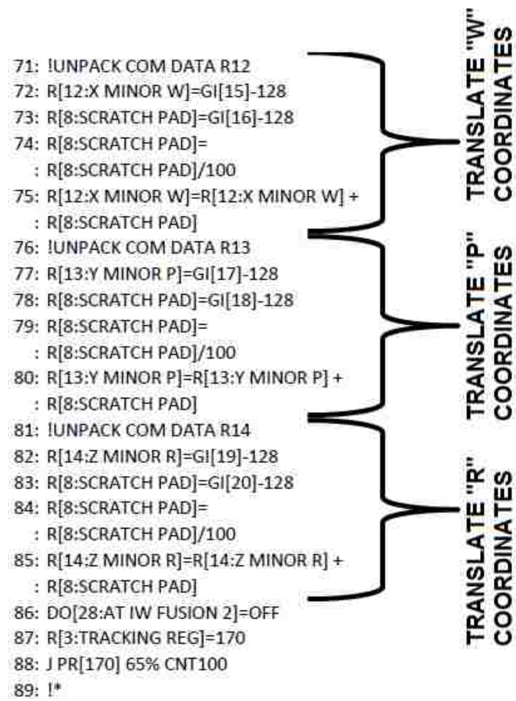


Figure 50-Robot Minor Axis Translations

Figure 49 illustrates the protocol for "unpacking" of the 8-bit data (0 … 256) received for the X, Y and Z position. As stated earlier, PLC cannot send or receive the data in decimal places, therefore data is broken into two sets of numbers; integer value before the decimal place, and integer value after the decimal place (camera programming section describes the reverse side of this formula in detail). Once this protocol is completed and the numbers are extracted, the two values are then added together and the coordinate location in decimal value is created. The same protocol is followed for the minor axes (shown in Figure 50).

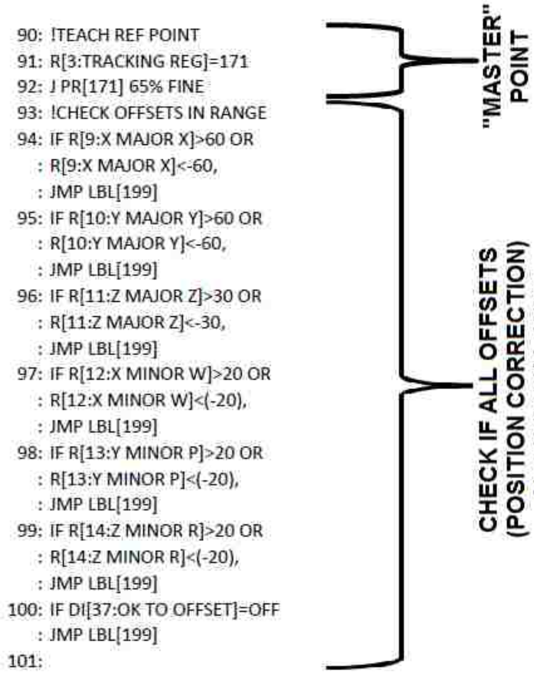


Figure 51-Robot "Master" Position and Offset Check

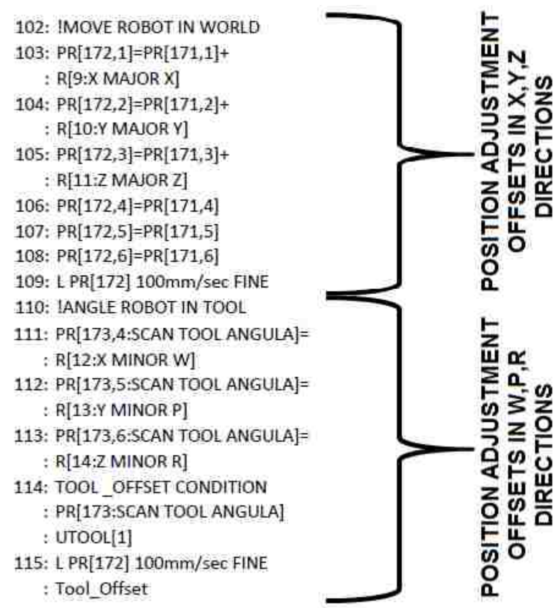


Figure 52-Robot Position Adjustment

Figure 51 identifies the "master" position PR[171] from which the position corrections take place in terms of robot offsets. This position is required to be recorded by bringing the tool center point of the EOAT to the feature location manually, every time a new product is introduced to the system or the system is going through the teaching sequence. Next part of the program assures that the values extracted from the camera fall within the offset limitations prior to making position adjustments. This section of the program is used as a redundancy check to eliminate any large position adjustments which may result in robot crash and/or equipment damage. Any values greater than specified in the program limits will generate a fault and stop the cycle. Succeeding program steps illustrated in Figure 52 demonstrate the position offsets in X, Y, and Z positions, followed by the angular adjustment in W, P, and R.

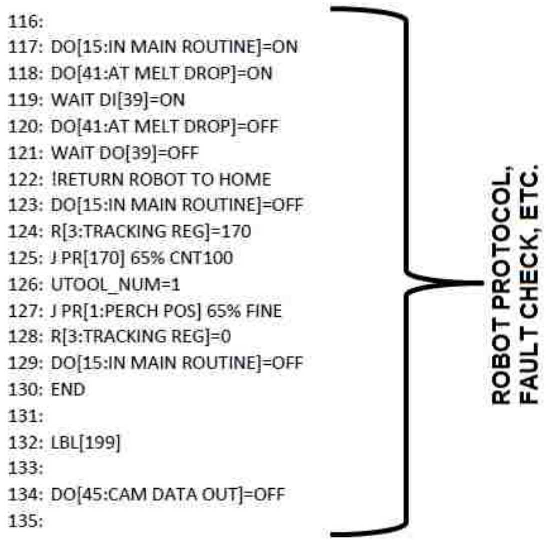


Figure 53-Robot Protocol

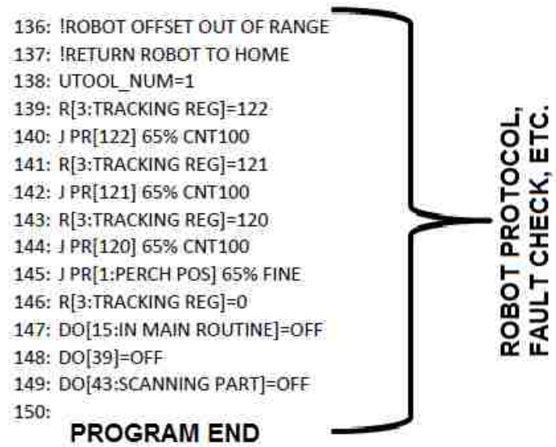


Figure 54-Robot Protocol

Figure 53 and Figure 54 finalize the robot program by using standard programming protocol.

4.5.2 Vision System

This section will describe the camera program as well as the techniques used in creating the program for the fuel tank case study.

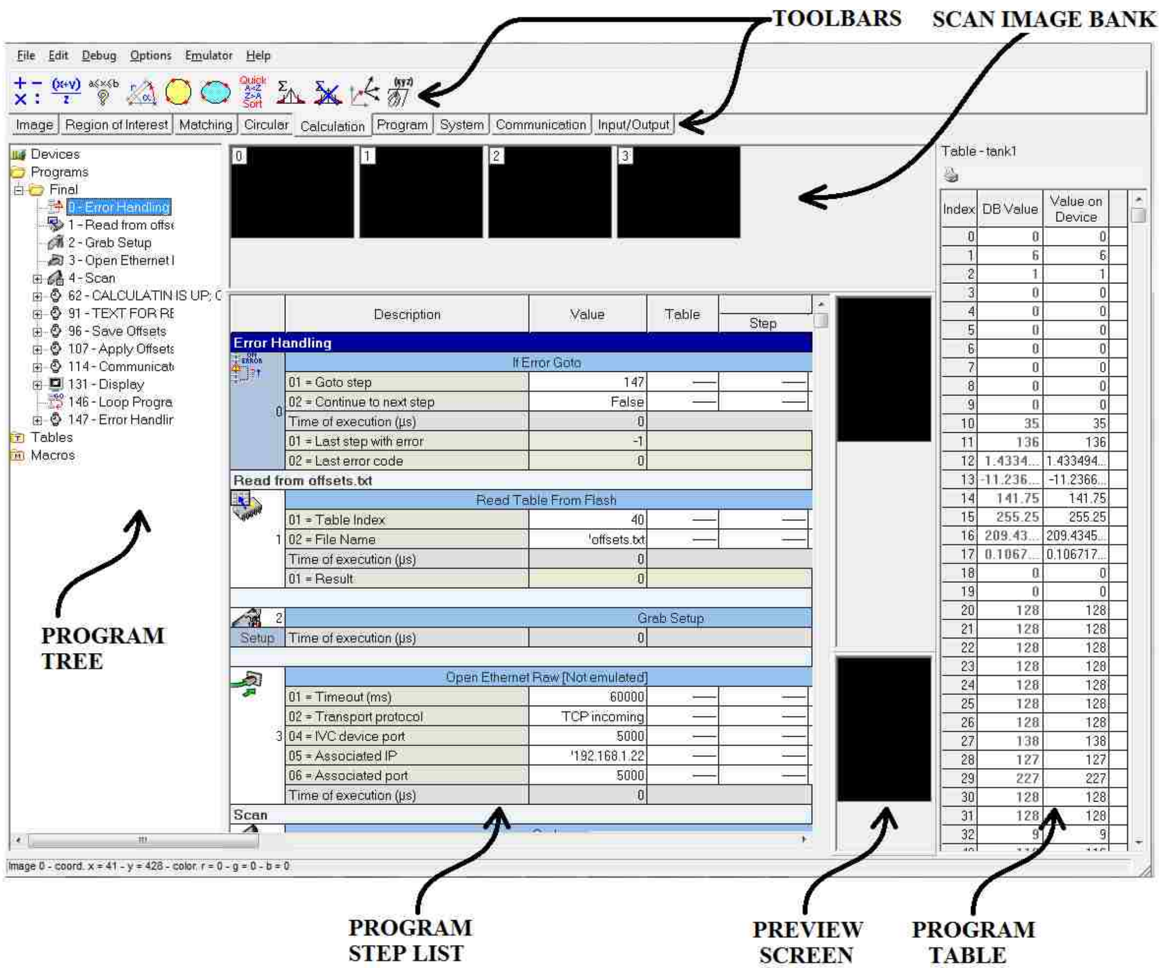


Figure 55-Camera Software Screen

Figure 55 illustrates the vision system software and the arrangement of tools used for creating the program. It consists of the program tree, toolbars, scanned image banks, preview screen, program steps and programming table.

As the image is scanned by the camera during the robot movement over the object, PLC byte is received from the PLC, at which time program starts its execution through the programming steps.

The first part of the program examines the image by analyzing a static region of interest (ROI) and by identifying the area where the examination of the features is taking place (Figure 56) by looking for a specific feature (i.e. hole).

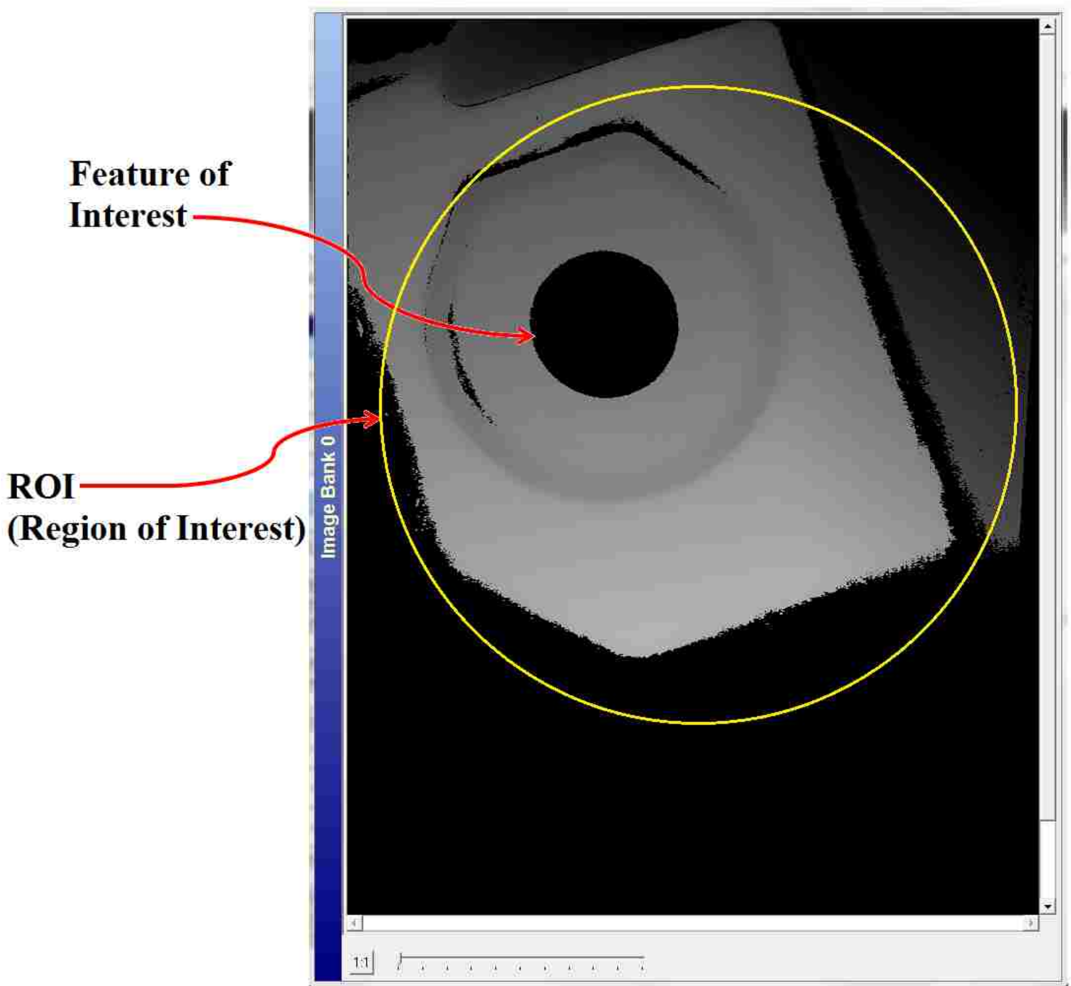


Figure 56-ROI Definition © 2017 IEEE

Once ROI step has been defined, Blob Finder tool can be utilized. This tool is used for analyzing the feature characteristics, and provides the centroid location as well as the feature size, to the table ID specified in the tool (Figure 57). This tool allows for the definition of size, depth and other feature parameters for the analysis. All features that do not fall within these parameters are automatically discarded. Blob Finder tool also provides limit values, which may be used to set the restrictions in part variation to avoid faults created by the objects outside of the geometry scope. Once the feature is identified, the parameters in terms of X and Y locations are exported to the program table and used in the next programming section.

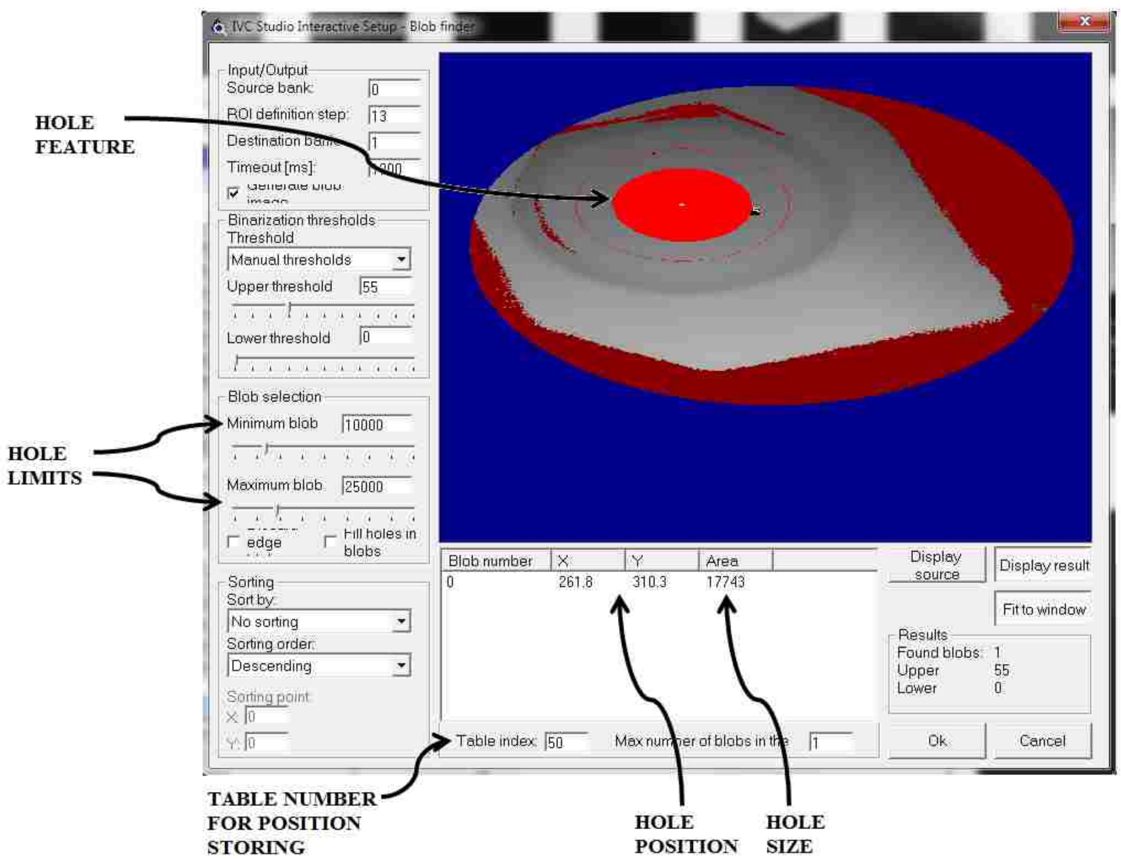


Figure 57-Blob Finder Tool © 2017 IEEE

By using the X, Y position provided by the previous step, two circles are placed (1 smaller and 1 bigger circle) with the centers corresponding to the same position. The area between these two circles represents the surface defined for placement of the “Best Fit Plane” which will be used for attaining the Z location of the feature (hole) in the next step.

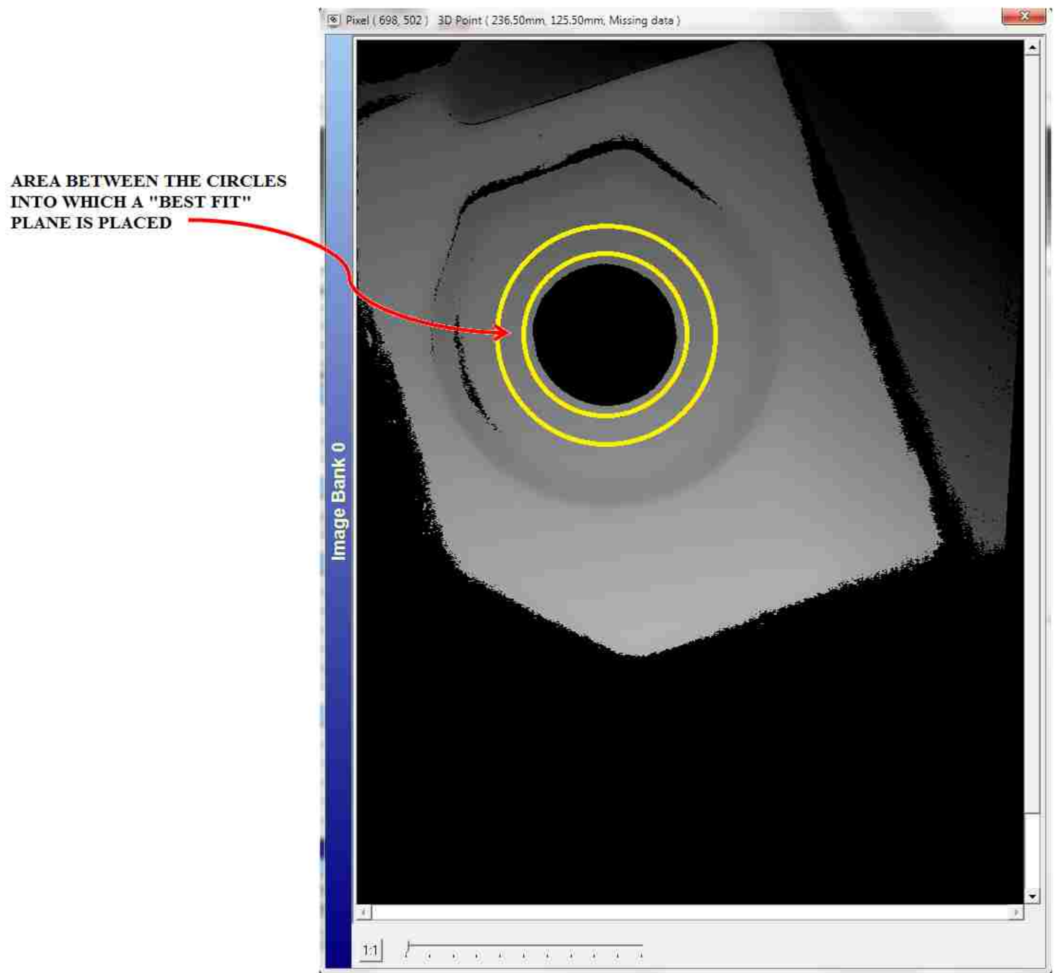


Figure 58-Methodology for Placing "Best Fit Plane"

This plane is called the "Best Fit" for a simple reason of analyzing the 3D surface and placing the plane on the surface that fits the best. Figure 59 shows an example of this methodology.

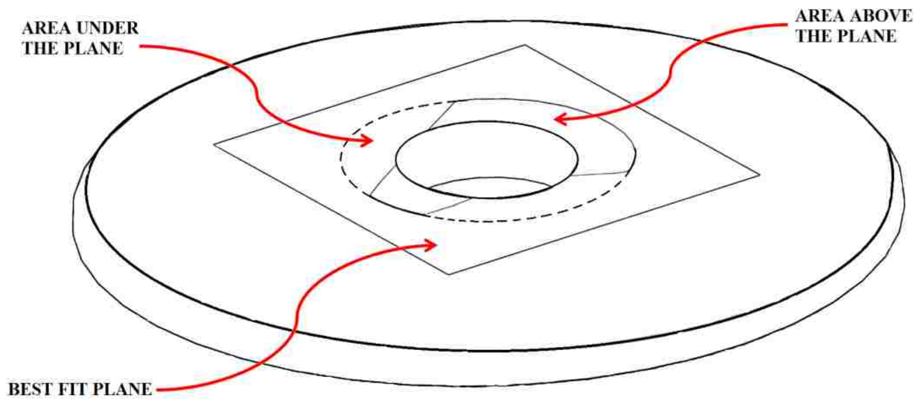


Figure 59-Best Fit Plane Placement on 3D Surface © 2017 IEEE

Once the plane is established, the next part of the program is developed to determine the plane angle in terms of roll and pitch in 3D space. As the X, Y position is already calculated and stored in the program table, the location will be pulled back into the program logic and placed into 02=Pixel X and 03=Pixel Y fields for each of the three steps as shown in Figure 60 below. This will provide calibrated Z position of the point.

POSITION ON BEST FIT PLANE IN THE X,Y HOLE CENTER

Midpoint				
	Get Calibrated Point			
48	01 = Source bank	2	—	—
	02 = Pixel X	=S44A3	—	—
	03 = Pixel Y	=S44A4	—	—
	04 = Filter type	No filter	—	—
	05 = Transform Data Block	-1	—	—
	Time of execution (µs)	0		
	01 = Calibrated X (mm)	236.75		
	02 = Calibrated Y (mm)	123		
	03 = Calibrated Z (mm)	184.3872		

POSITION ON BEST FIT PLANE 25mm ABOVE THE HOLE CENTER

Upper				
	Get Calibrated Point			
49	01 = Source bank	2	—	—
	02 = Pixel X	=S44A3	—	—
	03 = Pixel Y	=S44A4-100	—	—
	04 = Filter type	No filter	—	—
	05 = Transform Data Block	-1	—	—
	Time of execution (µs)	0		
	01 = Calibrated X (mm)	236.75		
	02 = Calibrated Y (mm)	98		
	03 = Calibrated Z (mm)	184.1507		

POSITION ON BEST FIT PLANE 25mm TO THE RIGHT OF THE HOLE CENTER

Right				
	Get Calibrated Point			
50	01 = Source bank	2	—	—
	02 = Pixel X	=S44A3+100	—	—
	03 = Pixel Y	=S44A4	—	—
	04 = Filter type	No filter	—	—
	05 = Transform Data Block	-1	—	—
	Time of execution (µs)	0		
	01 = Calibrated X (mm)	261.75		
	02 = Calibrated Y (mm)	123		
	03 = Calibrated Z (mm)	183.9218		

Figure 60-Compound Plane Angle Calculation

The first part of the program uses the X and Y position after which the position is extracted in the “Calibrated” field of each step, and X, Y and Z positions are calculated. Following two steps perform the same calculation, however, the position is calculated 25 mm above the hole center and 25 mm to the right of the hole on the best-fit plane. This provides 3 points in terms of X, Y, and Z positions, which are going to be used to calculate the plane angle (robot minor axes), by using trigonometry as shown in Figure 61 and Figure 62 below.

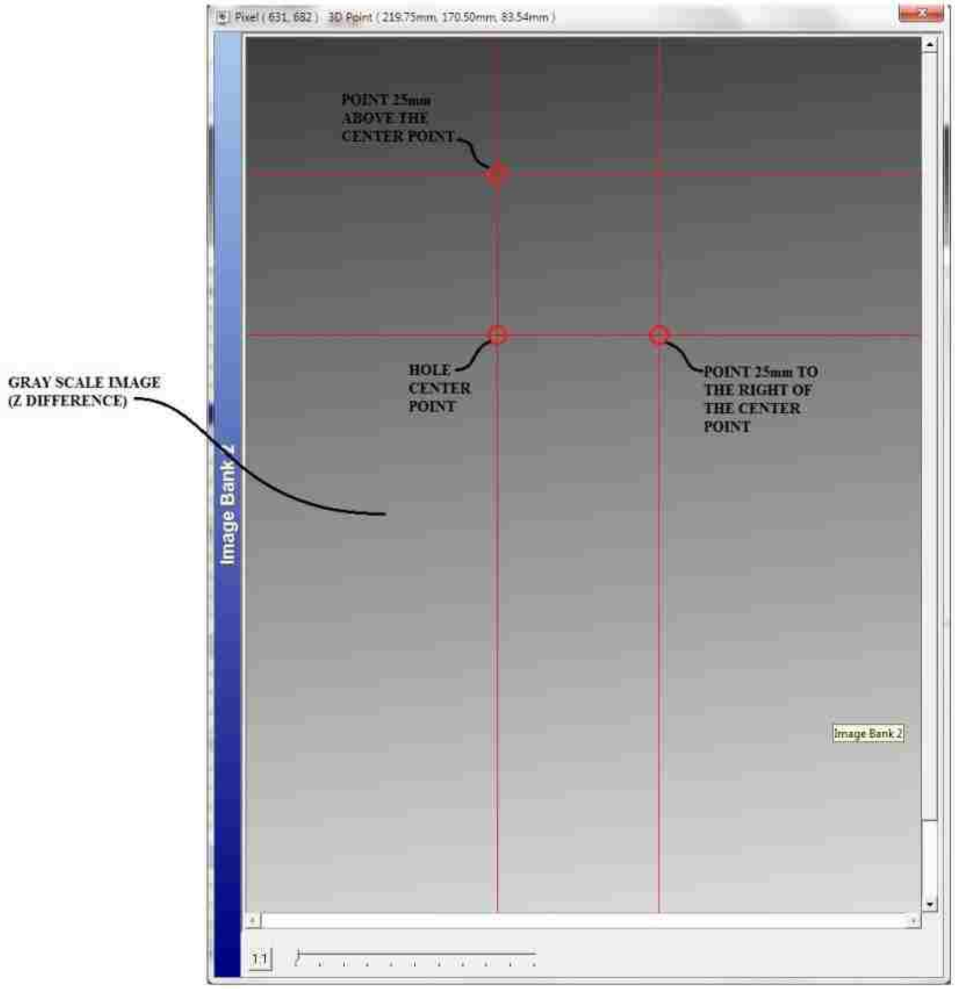


Figure 61-X and Y Minor Points Calculation © 2017 IEEE

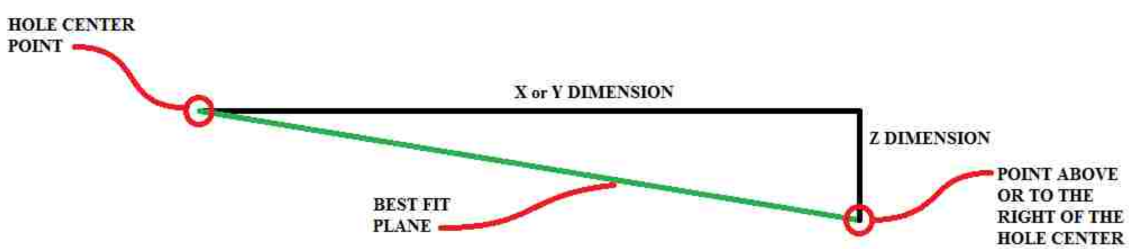
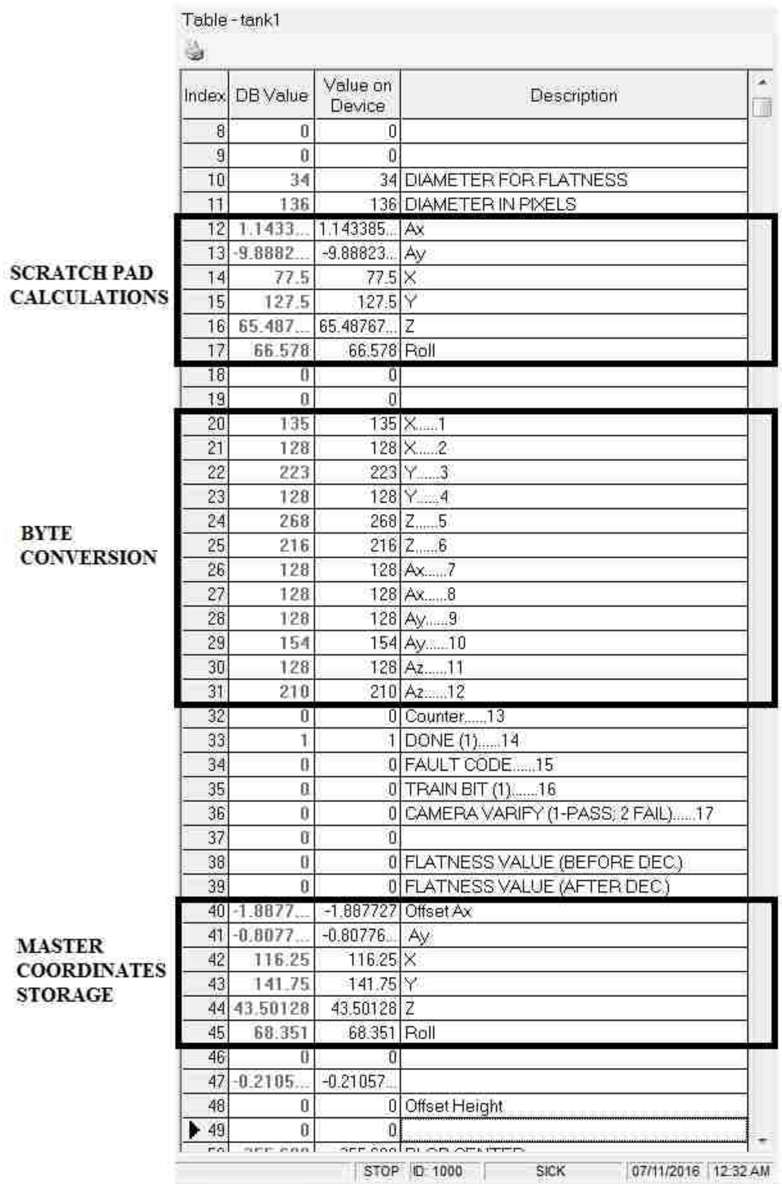


Figure 62-X and Y Minor Plane Calculation © 2017 IEEE

Though this is considered a compound angle plane, robot software does not provide calculations or a method for this position adjustment. In order to calculate this plane, robot software uses X and Y minor axis as shown in Figure 62 above. Therefore, camera algorithm was created to calculate minor X and Y angles separately.

Up to this point, the algorithm is able to calculate X, Y, Z positions, followed by W and P angles (R value may be calculated if the orientation feature is used for yaw angle) after which these values are saved to camera flash as the "master" coordinates, from which every other cycle will be monitored in terms of difference in position. For a subsequent scan, the program continues as explained below.

In the program structure master coordinates are saved to the camera flash but pulled back into the program and stored in the table rows 40 to 45, while the values being calculated are temporarily placed in the "scratch pad" rows 12-17 as shown in Figure 63.



Index	DB Value	Value on Device	Description
8	0	0	
9	0	0	
10	34	34	DIAMETER FOR FLATNESS
11	136	136	DIAMETER IN PIXELS
12	1.1433...	1.143385...	Ax
13	-9.8882...	-9.88823...	Ay
14	77.5	77.5	X
15	127.5	127.5	Y
16	65.487...	65.48767...	Z
17	66.578	66.578	Roll
18	0	0	
19	0	0	
20	135	135	X......1
21	128	128	X......2
22	223	223	Y......3
23	128	128	Y......4
24	268	268	Z......5
25	216	216	Z......6
26	128	128	Ax......7
27	128	128	Ax......8
28	128	128	Ay......9
29	154	154	Ay......10
30	128	128	Az......11
31	210	210	Az......12
32	0	0	Counter......13
33	1	1	DONE (1)......14
34	0	0	FAULT CODE......15
35	0	0	TRAIN BIT (1)......16
36	0	0	CAMERA VARIFY (1-PASS; 2 FAIL)......17
37	0	0	
38	0	0	FLATNESS VALUE (BEFORE DEC.)
39	0	0	FLATNESS VALUE (AFTER DEC.)
40	-1.8877...	-1.887727	Offset Ax
41	-0.8077...	-0.80776...	Ay
42	116.25	116.25	X
43	141.75	141.75	Y
44	43.50128	43.50128	Z
45	68.351	68.351	Roll
46	0	0	
47	-0.2105...	-0.21057...	
48	0	0	Offset Height
49	0	0	

Figure 63-Scratch Pad and Master Coordinate Placement

As the values being calculated are stored in the rows 12-17, they are also being used by the algorithm for comparison. The difference in each position is calculated and then stored in the same row overwriting the original values, thus giving these rows name "scratch pad".

Final values are then transferred to rows 20-31, after which they are sent to the PLC through the communication protocol. Prior to transferring the coordinates, these values are required to be translated into integers, as PLC cannot send or receive decimal values. Thus, only 8-bit values can be sent (0 … 256). This part of the algorithm will separate decimal values into 2 integer numbers (one before and one after decimal place). In order to generate this, the following formula and rules were developed:

The rule was set that value 128 (half point of 256 bytes) is considered as 0 value. All values over 128 are considered to be positive, while all values under 128 are considered negative. The formula below illustrates this example.

n1 *represents integer value before decimal, and* **n2** *represents integer value after decimal*

<u>To calculate **n1** value:</u>

$$n1 = [X] + 128 \tag{21}$$

<u>To calculate **n2** value:</u>

$$n2 = ((X-(n1-128) \times 100) + 128 \tag{22}$$

<u>*Example:*</u>

4.17

Integer value before decimal place:

4 + 128=***132***

Integer value after decimal place:

((4.17-(132-128)) x 100)+128=***145***

Therefore 4.17 is sent as two separate bytes; <u>132</u> and <u>145</u>.

The reverse side of this formula can be found in the robot program Figure 49 and Figure 50, as the robot is required to convert the values back into decimals in order to perform the position offsets.

Once all values are computed by the camera program, they are combined together (one after another) and sent to the PLC in form of a byte string, and subsequently to the robot.

Calculated position values are then displayed on the HMI screen for the personnel/technician’s reference, as shown in Figure 64 below.

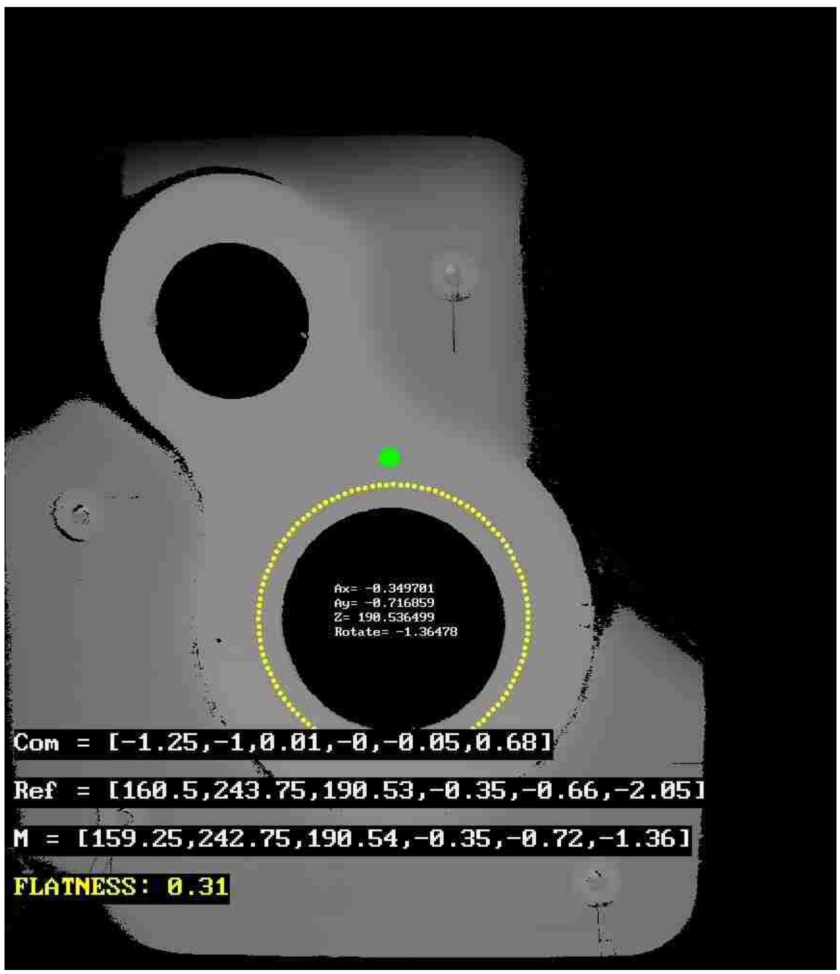


Figure 64-HMI Display

The values are separated into 3 rows which represent the following:

Ref- Represents the "master" position from where all other subsequent scan positions are measured.

M- Represents for the measured position of the scanned object.

Com- Represents communication offset values which are communicated to the robot. These values are the difference between the reference point and the position of the subsequent component.

4.5.3 PLC

The section on PLC programming will not be discussed in detail. Programming logic operates based on standard Siemens S7 function blocks, which are modified for the application of 3D vision system communication. The addition of this logic to the pre-existing system does not present a great significance in terms of research novelty, as the program logic for EOAT control is already present. More information on PLC program can be found in Appendix B.

4.6 Summary

This chapter provided a case study that presented a methodology, approach, and the implementation of the research to the fuel tank welding application. It demonstrated the device integration and the communication protocol between all components. The test procedure established the correlation between the robot and the image generated by the vision system in order to associate the two objects. The following chapter will encompass the system validation, accuracy, and test results. It will also cover improvements generated by the system.

CHAPTER 5: RESULTS, VALIDATION AND DISCUSSION

The following chapter is a summary of the test results which includes system accuracy. Robot programming and testing was performed under different scenarios, drawing conclusions on the system limitations.

5.1 Robot Validation

Robot manufacturers often publish only robot's repeatability as the robotic accuracy has not been yet fully developed to meet production needs (Fanuc Robotics America, 2017b). Robot accuracy is defined as robot's ability to move to the requested position and hitting the target each time, while the repeatability may be defined as moving to the same position repeatedly (Joubair, 2014) as illustrated in the figure below.

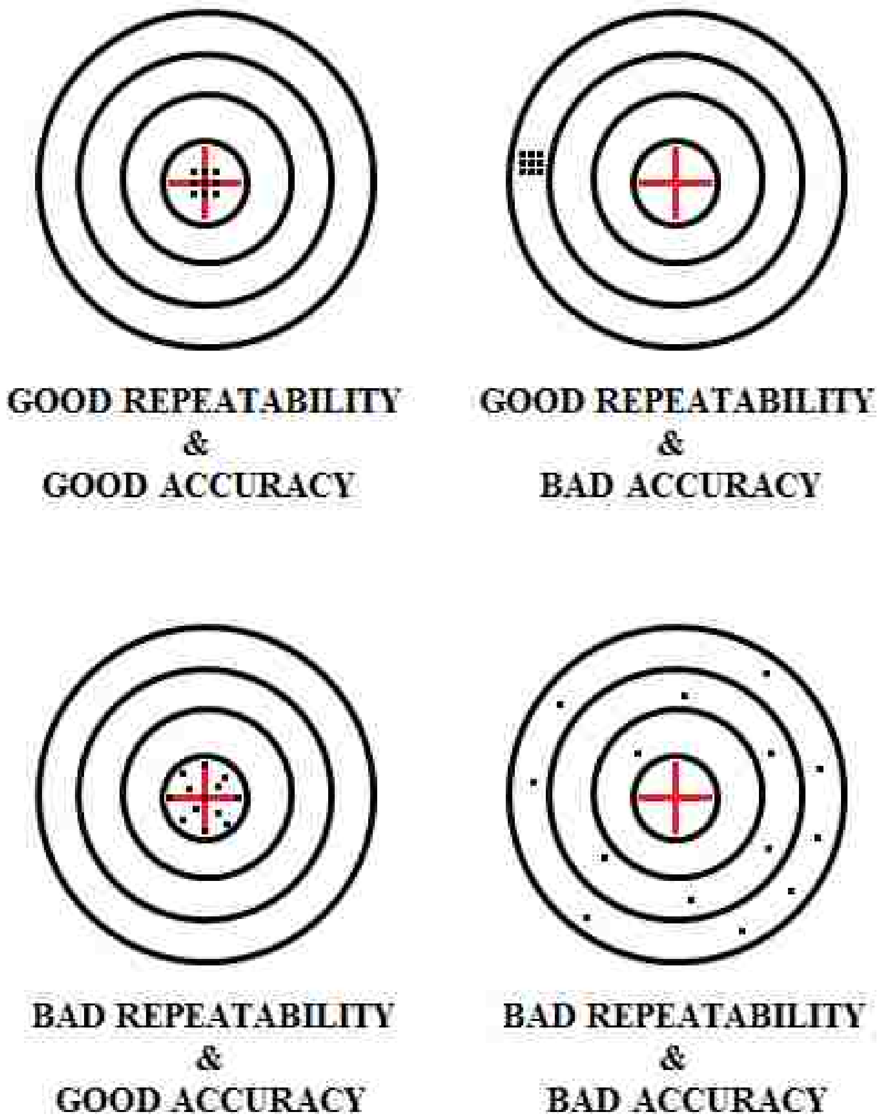


Figure 65-Robotic Accuracy and Repeatability Illustration

Robot accuracy depends largely on the EOAT weight and center of mass. The combination of joint positions and orientations with conjunction to the EOAT is referred to as the "pounce" position. This pounce position may be physically altered if different EOAT is placed on the robot and the position is measured and compared to the same position with the previous EOAT used.

As this research utilizes only 1 EOAT and relies on the on the technician to establish a first reference point by manually teaching the best EOAT position to the fuel tank surface, a first reference point is created from which the repeatability measurements will take place. Thus, system repeatability may be considered as accuracy.

Robot position in terms of readjustment was validated by monitoring tool center point (TCP) position displayed on the robot teach pendant. (Joubair, 2014)

Robot "master" position is stored as position register PR[171]. Position adjustment values send by the vision system are temporarily stored in robot registers R[9]-R[14]. Values from these registers are then added to the PR[171] resulting in PR[172] position which is initially generated by robot movement in X,Y,Z directions, followed by the W,P,R angles. Values from scan image (e.g. Figure 64) were used for validation.

PR[171] position was recorded as shown in Figure 66:

Table 8-PR[171] Position Coordinates (Master Position)

X=2043.774 mm	W=0.613 deg.
Y=339.205 mm	P=87.328 deg.
Z=495.297 mm	R=4.991 deg.

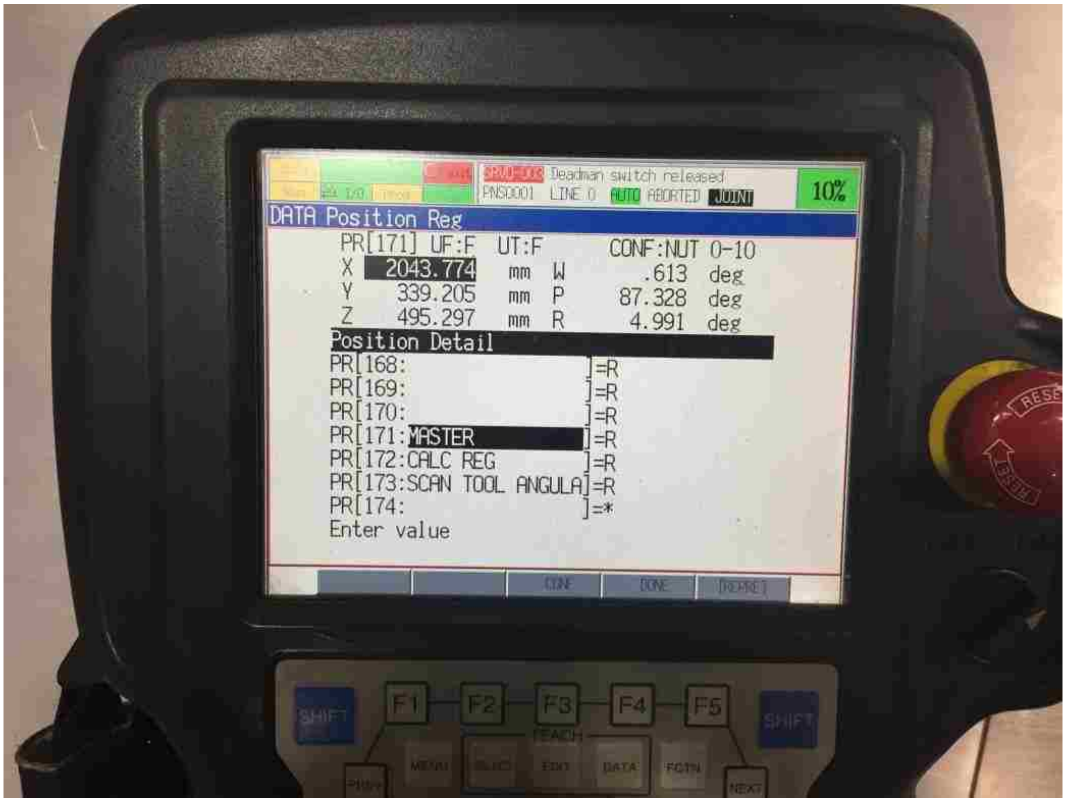


Figure 66-PR[171] Coordinates (Master Position)

Offset values from Figure 64 sent by the vision system are populated in robot registers as shown in Figure 67:

Table 9-Register Values (Position Offset Values) From Scan Image

R[9]= -1.25 mm	R[12]= 0 deg.
R[10]= -1.0 mm	R[13]= -0.05 deg.
R[11]= 0.01 mm	R[14]= 0.68 deg.

Figure 67-Register Values (Offset Values)

These values are the same values transferred from scanned image in Figure 64.

Register values (R[9] - R[14]) are then added to PR[171], resulting in PR[172] as shown in the Figure 68:

Table 10- PR[172] Position Coordinates (Offset Position)

X = 2043.774 + (-1.25) = **2042.524 mm**	W= 0.613 + 0 = **0.613 deg.**
Y= 339.205 + (-1.00) = **338.205 mm**	P= 87.328 + (-0.05) = **87.278 deg.**
Z= 495.297 + 0.01 = **495.307 mm**	R=4.991 + 0.68 = **5.671 deg.**

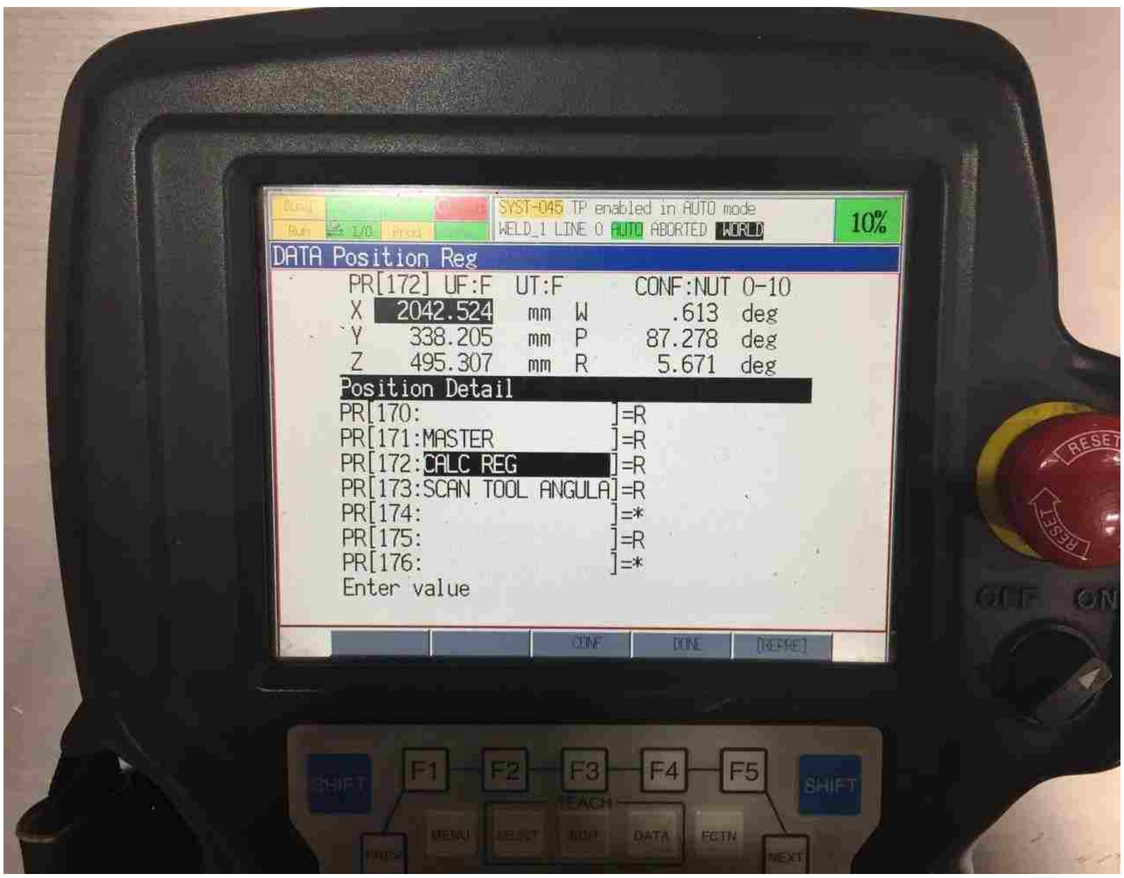


Figure 68-PR[172] Coordinates (Offset Position)

5.2 Camera Validation

To assure that the values are correct in terms of distance measurement provided by the camera, the device was manufactured in order to measure X, Y, and Z directions.

Figure 69-Verification Plate

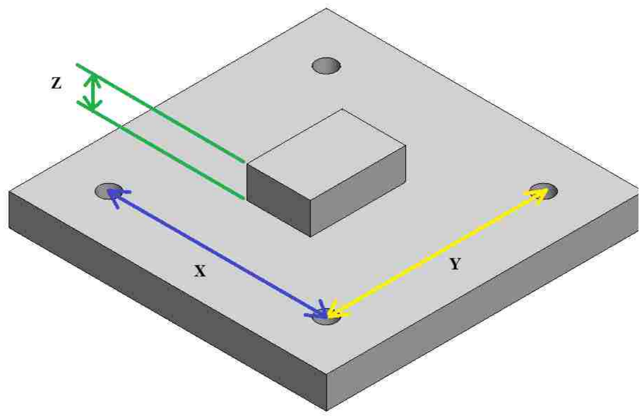


Figure 70-Verification Plate CAD Model

By obtaining distance values between the holes in X and Y direction from the camera, these values are then compared to the tolerance limit set in the camera program to the actual manufactured dimensions between the holes. The same procedure is then followed for the Z dimension (height). By obtaining X, Y and Z measurements by the camera, these values are then compared to actual manufactured dimensions in order to determine camera accuracy. Tolerance limit can be opened or closed depending on the manufacturing accuracy of the device.

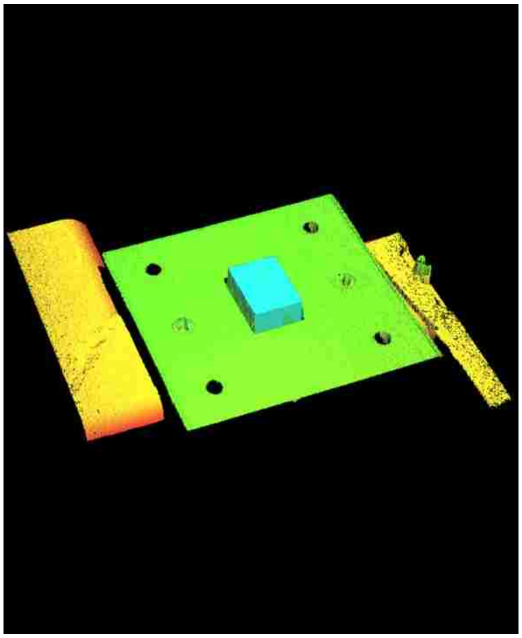


Figure 71-3D Scan of the Verification Device

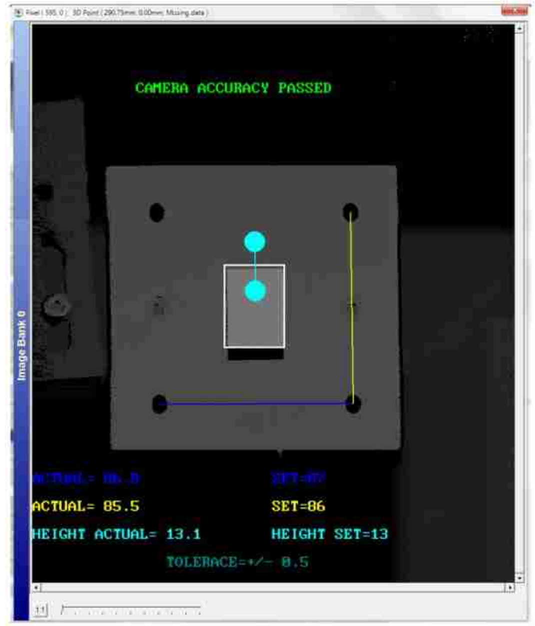


Figure 72-Verification Confirmation

Figure 72 illustrates the distance in X and Y directions between the 3 holes. Z distance is calculated by measuring the boss height to the base plate. If the distance measured is within the acceptable limits, the verification section is considered as pass, deeming the camera as accurate for processing.

This part of the program is activated by the PLC and can be programmed to activate after a certain number of cycles, beginning of every shift, or prior to every cycle. Passing the verification part of the program allows the program to advance with the sequence. It is imperative to note that the device present in Figure 69 was manufactured by hand using basic machine shop tools at disposal. The distance between the holes was not accurately machined, prompting for tolerance of ±0.5 mm. Repeatable scans showed that the values obtained varied within ±0.1 mm.

5.3 System Accuracy

System accuracy will include all components integrated together, thus providing the tolerance value for one complete system.

The test was performed by scanning a stationary fixed object (i.e. fuel tank section) 25 times without making any contact with the object after the scan. During this testing, 25 positions were recorded of the same stationary object to be used for accuracy calculation. Position offset values are shown in the table below and represent the variation between each scan. “Master” component was used in the test, providing [0,0,0,0,0,0] position as a measurement point from where every other subsequent scan is measured.

Position variation of the stationary object in X and Y direction would normally indicate that the scan activated by the robot was initiated too soon or too late from the encoder position. Performed test concluded this was not the case as values obtained remained as zero; proving that the scan start point was accurate and repeatable.

Position variation in Z direction may indicate that the scan path was too close or too far from the object (making the object seem closer or further away from the camera), or that the camera grayscale value calculated by the vision system carries a tolerance. Same reasoning for position variation in W, P, R direction may be applied.

Position offsets (“C” values) are shown in the table below and represent the variation between each scan.

Table 11-System Tolerance/Repeatability

SCAN Nr.	X	Y	Z	W	P	R
1	0	0	0.01	0	0.02	0
2	0	0	0.01	0.01	0.07	0
3	0	0	-0.02	0	0.02	0
4	0	0	0.01	0	0.06	0
5	0	0	0.02	0	0.05	0
6	0	0	0.01	0	0.09	0
7	0	0	0	0.01	0.03	0
8	0	0	-0.01	0	0.01	0
9	0	0	0	0	0	0
10	0	0	-0.08	0	0.03	0
11	0	0	0	0.01	0.05	0
12	0	0	0	0.01	0.02	0
13	0	0	-0.06	0	0	0
14	0	0	-0.06	0.02	0.05	0
15	0	0	-0.05	0	0	0
16	0	0	-0.04	0.01	0.07	0
17	0	0	-0.06	0.02	0.03	0
18	0	0	-0.04	0.01	0.06	0
19	0	0	-0.01	0.02	0	0
20	0	0	0.01	0	0.01	0
21	0	0	-0.03	0.01	0.02	0
22	0	0	0	0.01	0.05	0
23	0	0	-0.05	0.02	0.05	0
24	0	0	-0.06	0	0.04	0
25	0	0	-0.05	0	0.09	0
MIN. Value	0	0	-0.08	0	0	0
MAX. Value	0	0	0.02	0.02	0.09	0
Tolerance	**0**	**0**	**0.1**	**0.02**	**0.09**	**0**

Figure 73 offset values below are noted in scan#14 position as shown in Table 11.

Figure 73-Image Scan Repeatability Test

Using the maximum variation value of 0.1 mm noted in the Z direction, the system accuracy is stated as ±0.05 mm. The addition of this value to the theoretical robot position repeatability of ±0.2 mm, provides the complete system accuracy of ±0.25 mm in position.

Video of the system testing was recorded by 5 different cameras positioned at different angles around prototype cell. This included 2 of the cameras attached to the EOAT.

Video of the test as shown in Figure 74 is posted in the link below:

https://www.dropbox.com/s/1spf18s5l2n3daw/boris.mp4?dl=0

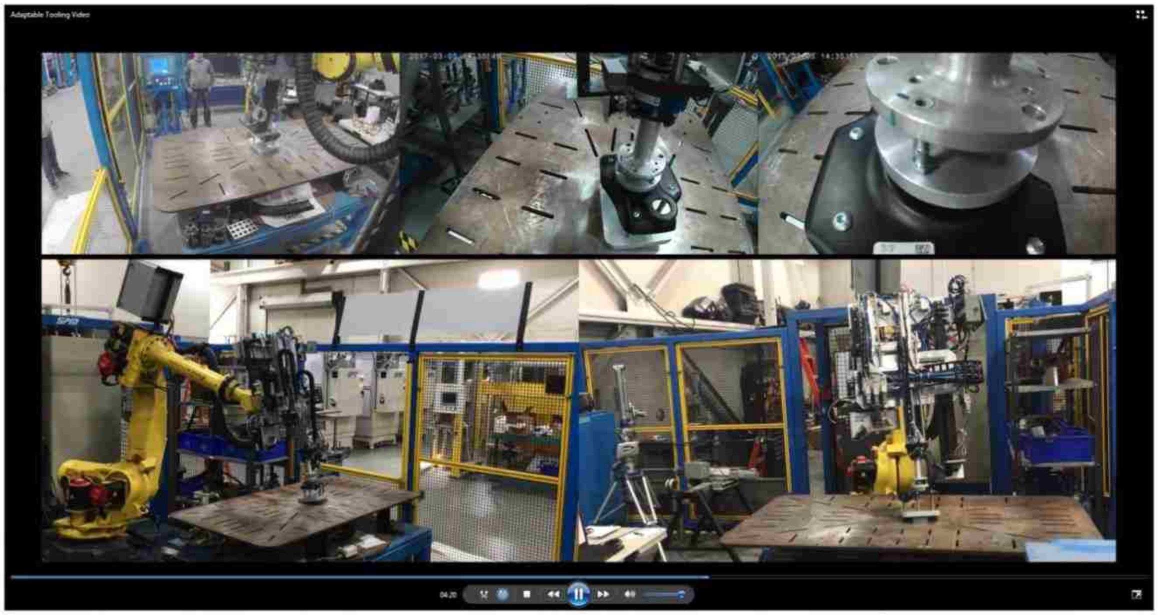


Figure 74-Test Video Image

5.4 Various Scenarios

Acknowledged as sensitive, it was imperative that the system is tested for different lighting scenarios present in the manufacturing settings. Different color flood lights (red, yellow and green) were applied directly to the object during the scan phase of the cycle. Lights were positioned at the distance of 150 mm away from the object and showed no impact on the image quality.

In addition to the lighting, another test by using markers on the fuel tank surface was implemented. White China marker was used to draw lines on the object prior to the scan in order to analyze if the direct color applied to the surface would have any effect on the image quality. This test showed no impact on the image quality.

Test performed by applying direct sunlight did indicate to have a major effect on the system in terms of the image quality. Section 6.3 on system limitations explains more.

5.5 System Comparison

This section will attempt to compare the outcomes/results of this research to some of the currently available vision guided robotic applications.

5.5.1 System Benchmark

Benchmarking this research to the existing systems proved to be very difficult, as outlined in the literature review section. Existing industrial systems do not go into any design detail, as system providers consider vision guided robotics a trade secret. Patents follow the same direction, by providing a minimal amount of information in the apprehension of reverse engineering.

The research was able to collect information on Fanuc iRVision 3DL system in order to create comparison in terms of cost and functionality.

Table 12-System Comparison

	Fanuc iRVision 3DL	**Thesis**
System Cost	$23,300	$15,950
Integration Cost	N/A	$19,000
Accuracy	±0.2	±0.25 mm
Ease of Use	Simple	Medium

Integration cost for iRVision was not listed in Table 12, as the industrial projects require a high degree of detail as well as the scope of work in order to get an accurate quote from the manufacturer. Thus, the cost for iRVision integration was not provided. The cost for thesis solution was available as SPM Automation recently provided integration quote for a system presented in the research.

The accuracy of the stand-alone iRVision system was not published at the time of this research. The system was referred to have a “high degree of accuracy” (Fanuc Robotics America, 2017a). Fanuc R-2000iC/165F robots which are most commonly equipped with the iRVision list the robot repeatability as ±0.2 mm. No comment of iRVision system integration having an effect on this tolerance is mentioned in this specification.

Ease of use regarding programming provides Fanuc with an advantage over the proposed system. Interactive programming screens and tools on the robot controller allow the users to use only one software for robot and camera programming, completely eliminating the PLC. Presented research uses 3 different software packages (PLC, robot and vision system) for the same solution. The elimination of extra software makes Fanuc system easier to use for the certain applications (e.g. material handling) where PLC is not required to monitor and check for certain values.

Assuming the equal cost for integration of the two systems, both systems present a practical solution for solving part to part variation issues. The system presented in the thesis shows lower cost compared to the Fanuc solution. However, Fanuc system provides a simpler solution regarding the initial implementation and maintenance due to the exclusion of the PLC and separate vision system programming. In conclusion, this provides system integrators and/or end users with 2 feasible options to choose from depending on their capability and/or budget.

5.5.2 Cycle Time

Data collected on welding Inlet Check Valve (ICV) component was gathered by contacting existing fuel tank manufacturing plants such as YAPP Automotive System and Kautex Textron.

Average cycle time was determined at 45 seconds as the component size varies and larger surface area requires longer melt time. Comparing this cycle time to the test results of 34 seconds, cycle time reduction of 25% is achieved (Table 13).

Table 13-Cycle Time Comparison (Conventional vs Research Solution)

	Conventional	**Thesis Solution**
Average Cycle Time	45 sec	34 sec

5.5.3 Weld Quality

Weld quality cannot be quantified due to lack of information released by the manufacturing facilities. Prevailing scrap rate frequently set by the manufacturing facilities is at 4%, therefore this number can be expected to be reduced, as the research provides ideal tool positioning.

5.5.4 Personnel Cost Reduction

Personnel cost reduction is another factor which cannot be quantified without detailed data collection and research at the manufacturing facility. This improvement will remain to be calculated in terms of personnel reduction percentage as the system gets implemented.

5.5.5 Communication Option

Eliminating PLC device and establishing the communication between the robot and the vision system directly is possible, however, it was not investigated as this option is not preferred for an industrial application which requires a set of safety redundancy. PLC device is used as a master device to assure that when a specific program is called to perform (e.g. weld ICV, validation plate, etc.) it does indeed execute. This is required when multiple objects are being analyzed by the system and not a single operation. It is also used to assure that the values sent by the camera are a new set of data calculated and not previous scan results. In addition to this, it is also used to monitor a variation between the objects and collect this data for analyzing at a later date. Thus, unless the system is used for an experiment outside of the production environment or being used for a single application which may not require a set of safety checks, utilizing PLC device is recommended.

5.6 System Architecture

The figure below illustrates the system architecture in terms of control structure and device communication used in this research.

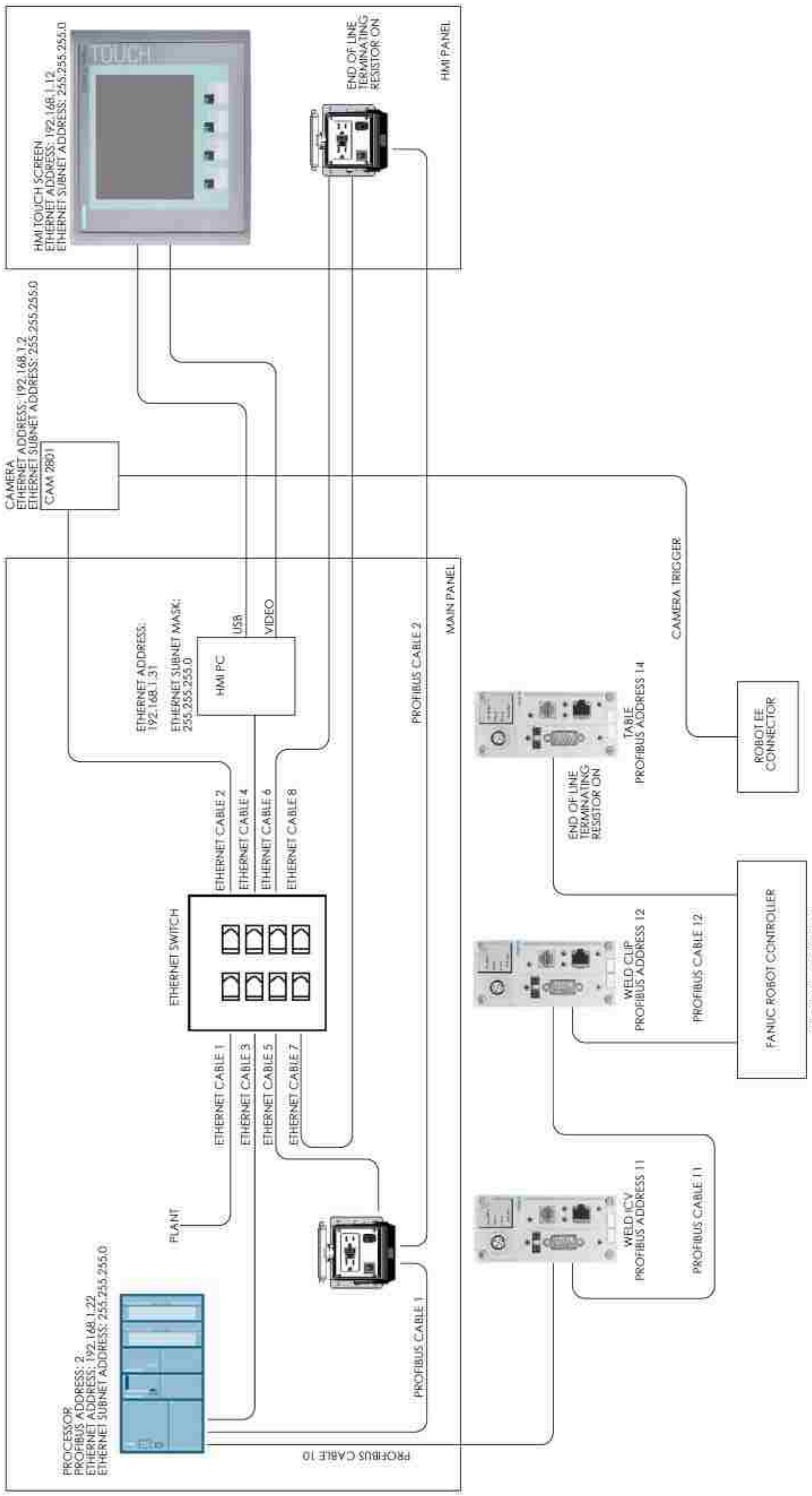


Figure 75-System Architecture

5.7 System Configurations

Research used a specific approach best suited for the fuel tank manufacturing industry. Vision system was mounted on the robot EOAT in order to easier manipulate the camera position around the fuel tank and take images of various regions of interest. This approach was used due to the fuel tank manufacturing equipment guidelines set by Tier 1 suppliers.

However, the system could also be configured with the fuel tank fixture used as the EOAT, while the camera and the processing unit are fixed in the machine; essentially reversing the components positions. With this approach, the robot can move the fuel tank in front of the camera to perform a scan. Once the scan is completed, the fuel tank can then be repositioned in front of the processing unit to perform the welding operations. This option was not tested or explored but may present a feasible solution for some scenarios.

5.8 System Design Guidelines

In order for the system to perform and function as specified in the thesis research, the following guidelines should be followed. This is particularly critical on the robot programming side, as the repeatable image scan start position is very important. Non-repeatable scan start position will generate incorrect object position relative to robot EOAT tool center point.

ROBOT

- 6 DoF
- Minimum repeatability specified ±0.2 mm
- Create and test program for accurate scan start position by scanning the same object over and comparing the positon results as outline in section 5.3
- Use encoder position values to start the scan as grater (>) or smaller (<) than scan start position value defined. Using exact value in the program may not active the scan signal every time, as the encoder value jumps through decimal points during robot movement. Thus, this value may be missed if specific.
- Assure that all offset values are applied in correct directions, as camera and EOAT may have different user tool coordinates

CAMERA

- SICK IVC-3Dxxxxx series
- Chose the camera by examining the features such as working distance from the object
- Create 3D validation device to assure that camera values measured are within limits
- Assure camera mounting is repeatable in the case of removal.
- In case of camera removal, system should go through "mastering" sequence as the correlation between the camera and the robot may be lost
- Use torsion cables for Ethernet communication between camera and PLC due to robot movement

PLC

- Siemens S7
- Ethernet and Profibus communication
- Utilize standard function blocks (FB) for programming
- Use different function blocks for communication, operations, faults, etc.
- Monitor system to assure that new data is sent by the camera every time

- Utilize program to switch coordinate directions (e.g. X and Z) in case of robot movement in the wrong direction, as robot and camera may have different user tool coordinates

CHAPTER 6: CONCLUSION AND FUTURE WORK

6.1 Research Contribution

This research introduced a novel approach and created a model for solving production issues created by part variations. This approach outlines a method for utilizing existing capital equipment and integrating a 3D vision system. It can be used for most applications where the position of components may vary, and the feature can be clearly defined in the image scan. This approach introduces the methodology for using a vision system and associating it with the robot EOAT to establish a correlation in 3D space. By using the proposed approach to account for part variation, the system can be customized for each application and tested for different elements. It may also be used to monitor and provide information regarding part quality prior to processing, thus making it versatile.

6.2 Significance

As the presented research focuses on an industrial application, the potential significance presented herein includes:

- Automatic adaptation of robot mounted processing unit for part variations
- Capability to simplify component fixturing by eliminating the consideration for the magnitude and direction of shrink of the plastic fuel tank during manufacturing
- Ability to provide fuel tank manufacturers with more flexibility in terms of hermetically welded component locations (distancing hermetic weld positions from the 4-way isostatic element)

- Increasing OEE (Overall Equipment Effectiveness) by eliminating downtime, increasing output, and eliminating scrap
- Elimination of equipment setup cost due to process changes
- Overall production cost reduction
- Elimination of manufacturing inconsistencies in terms of final product quality
- Cycle time reduction by creating ideal conditions for fuel tank welding
- Minimizing equipment setup during installation due to an unstable manufacturing process

6.3 System Limitations

During the system testing and development, different environmental conditions were applied. It was concluded that direct sunlight exposure to the component surface creates "noise" on the image, making it very difficult to process. An example of the same object with and without direct sunlight exposure is shown in Figure 76 and Figure 77 below.

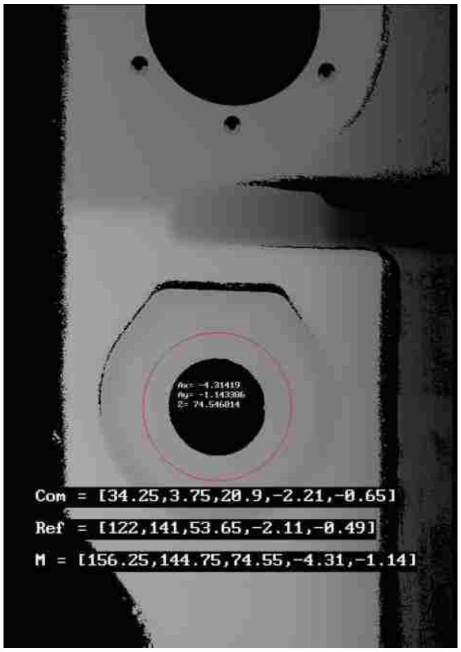


Figure 76-Scan Without Direct Sun Light Exposure

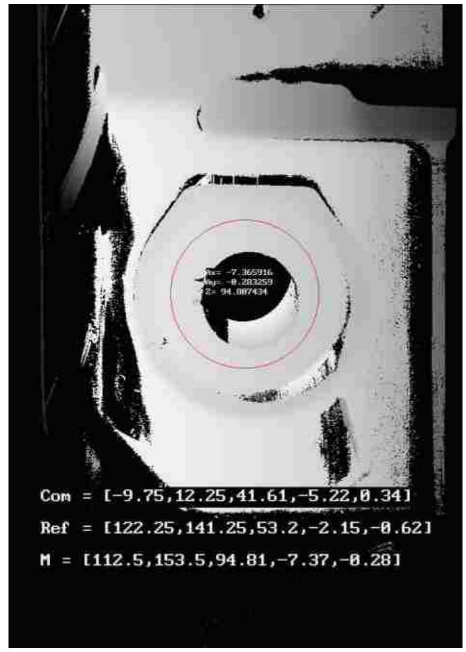


Figure 77-Scan Affected by Direct Sun Light Exposure

Other light colours (flashing and non-flashing) as well as surface paints have also been tested on the component surface and did not show to have any impact on the image in terms of distortion. A solution to overcome the direct sunlight problem is to create a shadow on the object surface. During the research, a cardboard panel was placed on the machine guard to create a shadow in the work envelope, which eliminated the problem.

Another system limitation is the amount of tilt that may be applied to the object. Excessive object angle will shift the hole center, and transform the circular shape of the hole into an oval. An object with 6.4 mm thickness (comparable to the fuel tank wall thickness) was simulated in CAD at 30° angle tilt in order to illustrate the effect of surface tilt on the fuel tank surface. Applying this angle shifted the hole center by 1.6 mm. Increasing the wall thickness will result in greater feature position shift, as the circular feature becomes increasingly oval. Figure 78 illustrates this limitation.

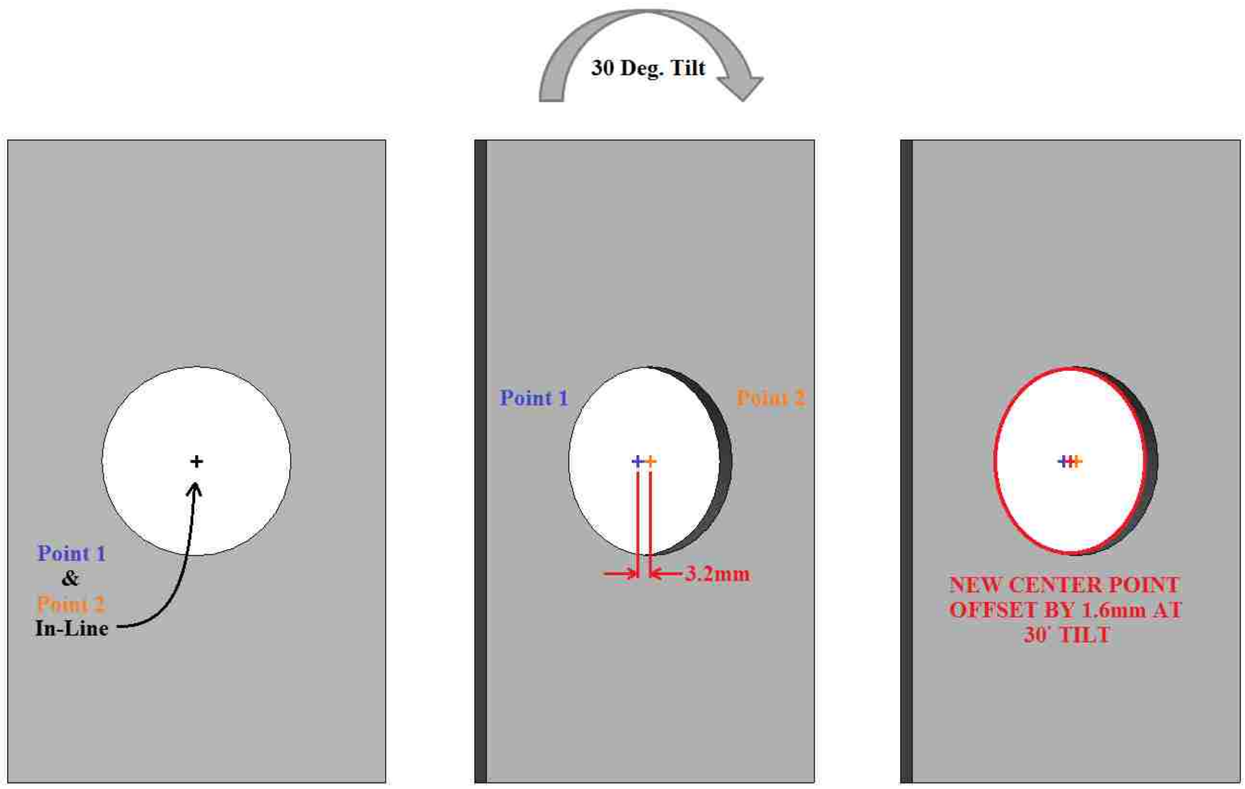


Figure 78-Object Tilt Illustrating Hole Offset in 3D CAD

At this point in the system development stage, these two limitations are the only identified restrictions on system performance. The results presented were specific to this thesis research on solving part to part variation related to plastic fuel tank welding applications.

6.4 Conclusion

The design process regarding an adaptable tooling system for part-to-part variation processing is presented in this thesis to help engineers develop equipment for solving part variation issues in the production environment. The same procedure may be used for pick and place applications. Chapter 1 provided current industrial practice, identifying the constrains in the fuel tank manufacturing process, which resulted in the research motivation and objective. Chapter 2 presented a literature survey covering academia, patents, state-of-the-practice, and state-of-the-art. Each section was reviewed to identify missing gaps, which resulted in this research. Chapter 3 provided a design process used for the system development and the method structure. Chapter 4 presented a case study, utilizing actual industrial components and equipment to support and verify the methodology. The results and validation of this case study were covered in Chapter 5. Research contributions, significance, and limitations are presented in Chapter 6.

The proposed system design covered in this thesis requires the programming and integration of PLC, vision system, and robot to produce a system, which is adaptable to part position variation. Combined as one, the structure is classified as a vision guided robotic (VGR) system, which can be applied to different manufacturing processes.

Commonly, manufacturing plants are required to retire existing older robots to make room for new VGR systems, as the older equipment does not support software upgrades to make them VGR compatible. With the proposed system, manufacturing facilities are presented with an option of utilizing existing equipment, i.e., robots, in order to create a VGR system, thus eliminating large investments.

The system was validated and tested at SPM Automation Inc., Windsor, ON, and resulted in 3 patent applications:

- US 2017/0038756 A1 -METHOD OF SELF-ADJUSTING A MACHINE TO COMPENSATE FOR PART-TO-PART VARIATIONS
- US 2017/0038757 A1 -MACHINE FOR SELF-ADJUSTING ITS OPERATION TO COMPENSATE FOR PART-TO-PART VARIATIONS
- CA 2937951 A1 -MACHINE AND METHOD OF SELF-ADJUSTMENT TO COMPENSATE FOR PART-TO-PART VARIATIONS

6.5 Future Work

The system proposed in this thesis research is a new method of improving production output, and as such, it is still being investigated for other limitations. In terms of system potential, researching flatness measurement of the fuel tank surface can create an opportunity for automatic parameter adjustment by manipulating the matching/heating time of the fuel tank surface to further minimize the cycle time. Regarding parameter adjustments, i.e., hole size and position, HMI interactive setup screen development should be investigated to allow for simple setup adjustments.

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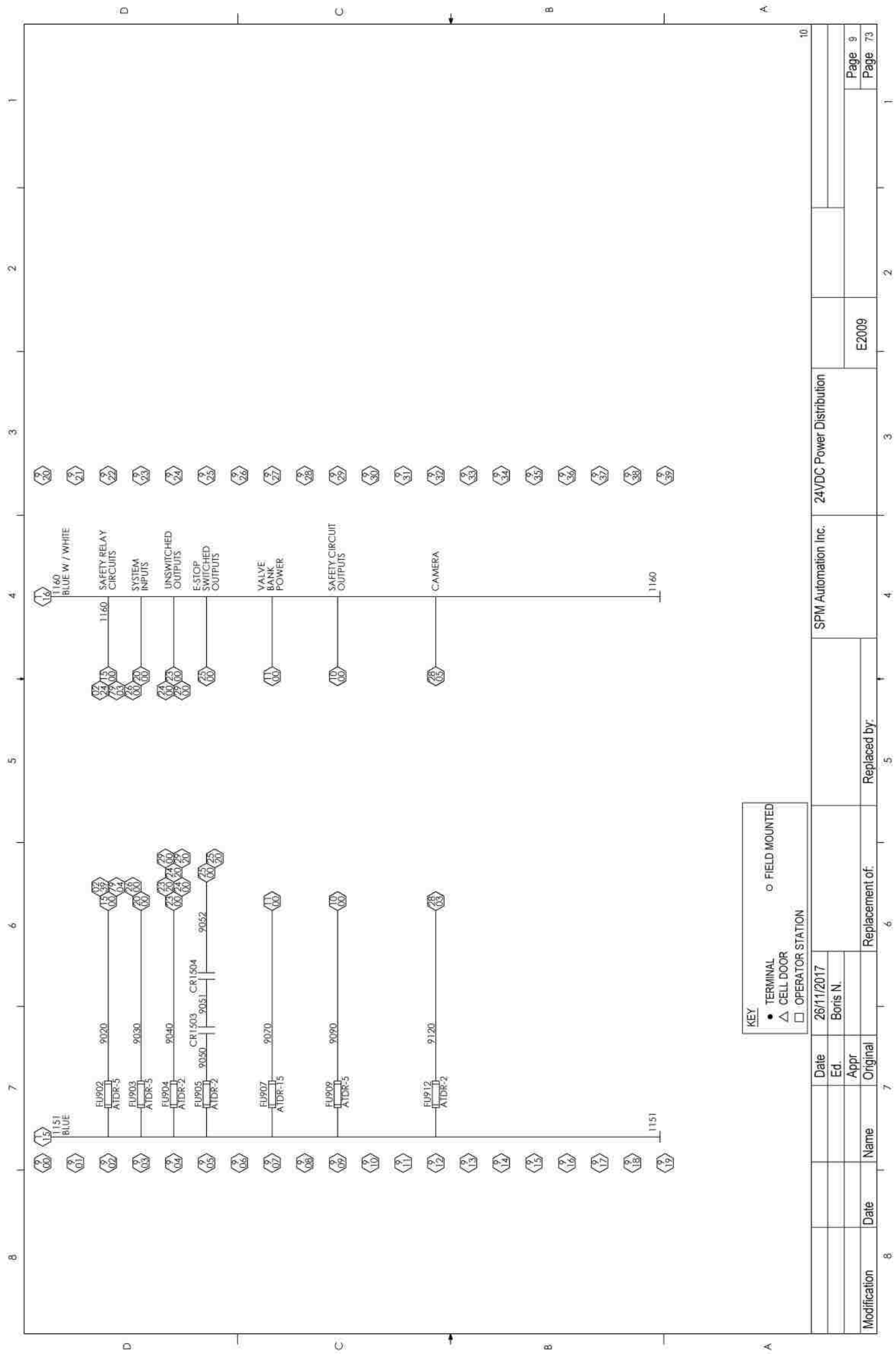
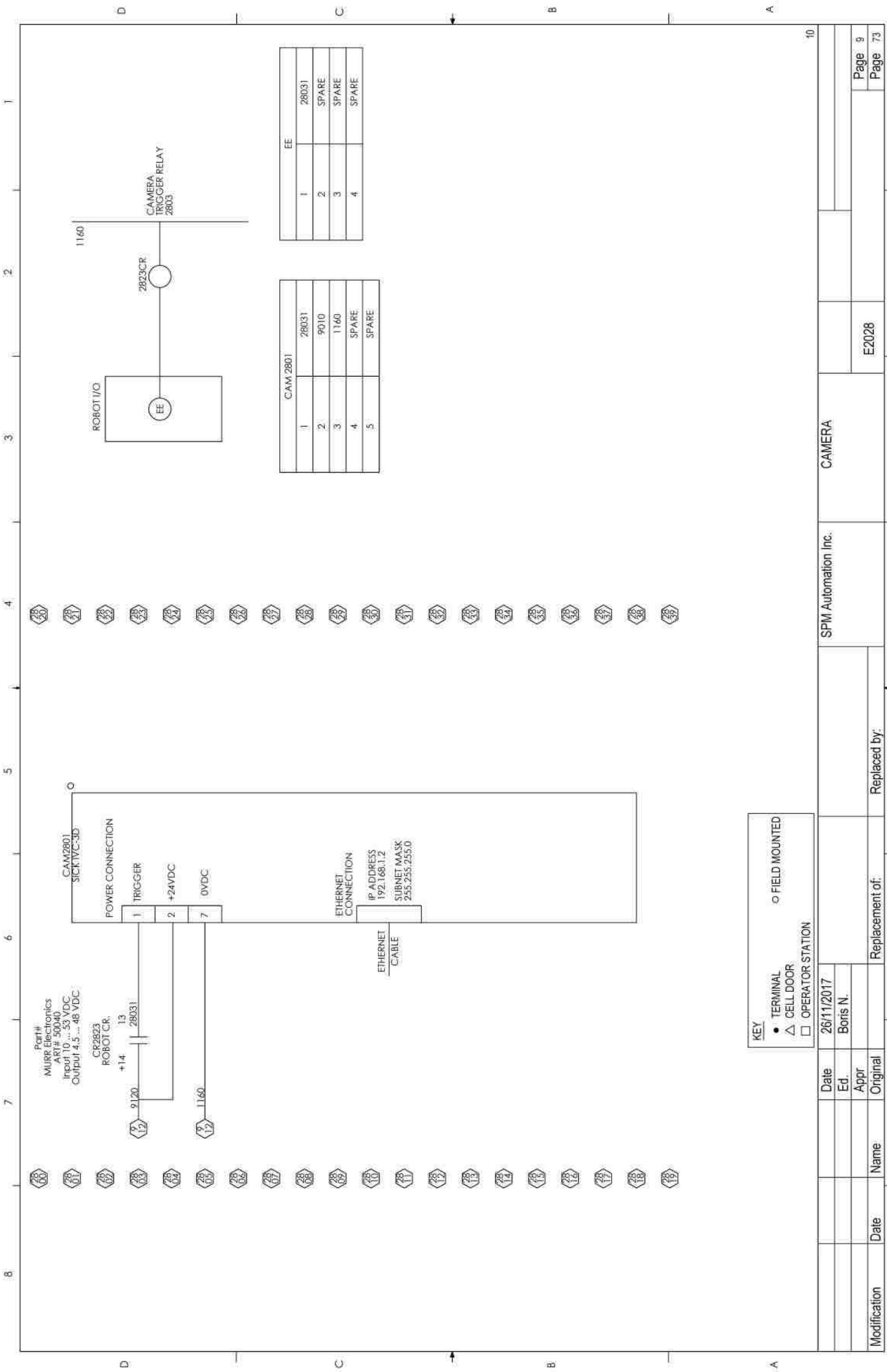
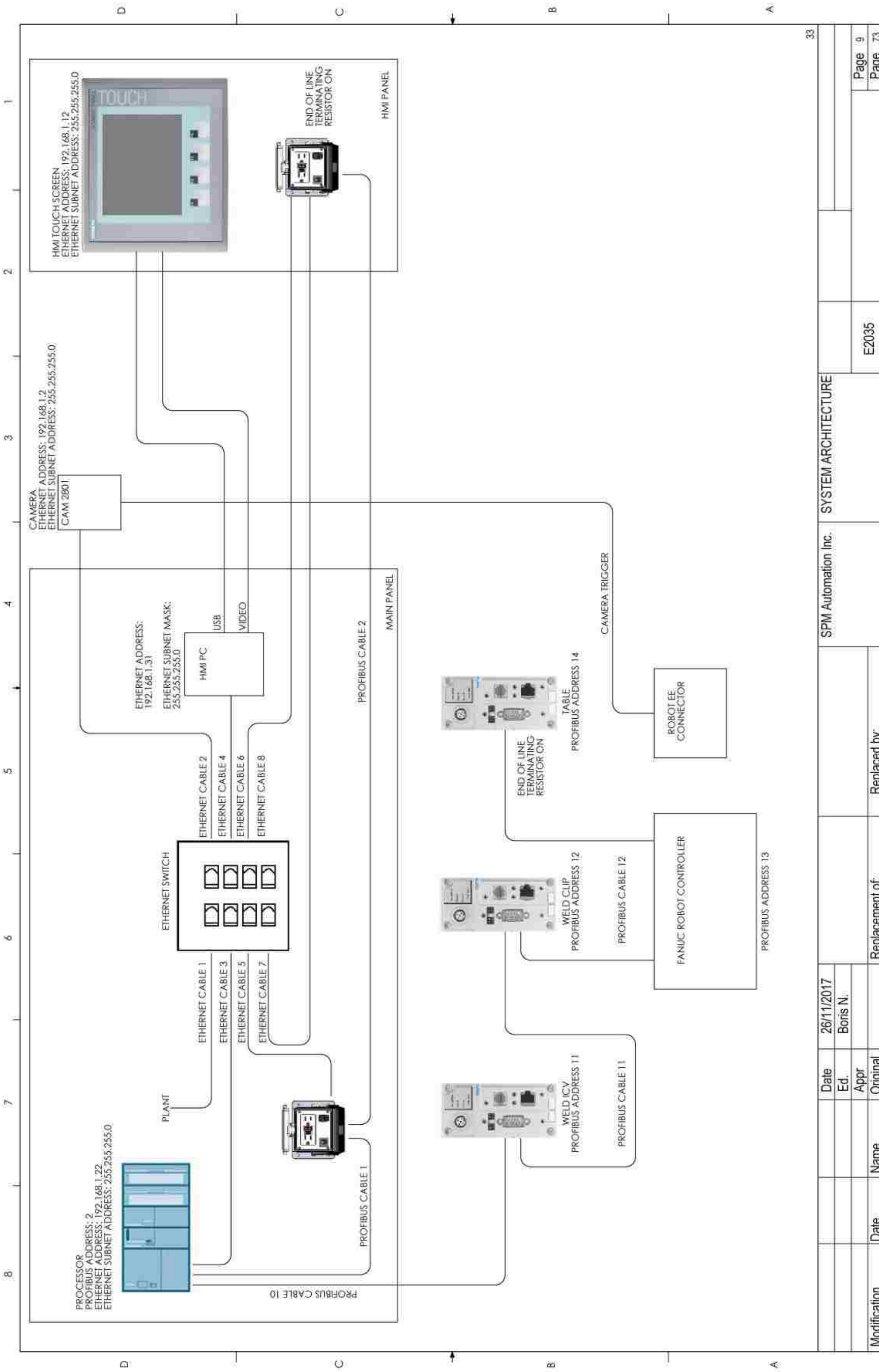
APPENDIX A: Electrical Drawings





CAM 2801	
1	28031
2	9010
3	1160
4	SPARE
5	SPARE

EE	
1	28031
2	SPARE
3	SPARE
4	SPARE


HMI TOUCH SCREEN
ETHERNET ADDRESS: 192.168.1.12
ETHERNET SUBNET ADDRESS: 255.255.255.0
TOUCH
END OF LINE
TERMINATING
RESISTOR ON
HMI PANEL
CAMERA
ETHERNET ADDRESS: 192.168.1.2
ETHERNET SUBNET ADDRESS: 255.255.255.0
CAM 2801
CAMERA TRIGGER
ROBOT EE
CONNECTOR
MAIN PANEL
ETHERNET ADDRESS:
192.168.1.31
ETHERNET SUBNET MASK:
255.255.255.0
HMI PC
USB
VIDEO
PROFIBUS CABLE 2
ETHERNET SWITCH
ETHERNET CABLE 2
ETHERNET CABLE 4
ETHERNET CABLE 6
ETHERNET CABLE 8
ETHERNET CABLE 1
ETHERNET CABLE 3
ETHERNET CABLE 5
ETHERNET CABLE 7
PLANT
PROCESSOR
PROFIBUS ADDRESS: 2
ETHERNET ADDRESS: 192.168.1.22
ETHERNET SUBNET ADDRESS: 255.255.255.0
PROFIBUS CABLE 1
PROFIBUS CABLE 10
TABLE
PROFIBUS ADDRESS 14
END OF LINE
TERMINATING
RESISTOR ON
WELD CLIP
PROFIBUS ADDRESS 12
PROFIBUS CABLE 12
FANUC ROBOT CONTROLLER
PROFIBUS ADDRESS 13
WELD ICV
PROFIBUS ADDRESS 11
PROFIBUS CABLE 11
SPM Automation Inc.
SYSTEM ARCHITECTURE
E2035
33
Page 9
Page 73
Date 26/11/2017
Ed. Boris N.
Appr
Original
Replacement of:
Replaced by:
Modification
Date
Name
1
2
3
4
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7
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A
B
C
D

APPENDIX B: PLC Program for Camera Communication

FB97 - <offline>

"R1 Camera Send/Re TCP"

Name: **Family:**
Author: **Version:** 1.4
Block version: 2
Time stamp Code: 08/11/2013 03:38:19 PM
Interface: 05/16/2011 07:19:49 PM
Lengths (block/logic/data): 01562 01124 00028

Name	Data Type	Address	Initial Value	Comment
IN		0.0		
INIT_COM	Bool	0.0	FALSE	
OUT		0.0		
IN_OUT		0.0		
STAT		0.0		
T_SEND	TSEND	2.0		
T_RCV	TRCV	24.0		
T_CON	TCON	48.0		
T_DISCON	TDISCON	68.0		
T_PARAM	TCON_PAR	78.0		
C1	Struct	142.0		
ID	Word	142.0	W#16#0	
CONNECTED	Bool	144.0	FALSE	
CONN_DONE	Bool	144.1	FALSE	
CONN_BUSY	Bool	144.2	FALSE	
CONN_ERROR	Bool	144.3	FALSE	
CONN_SETA	Bool	144.4	FALSE	
DISCONNECT	Bool	144.5	FALSE	
CONN_STATUS	Word	146.0	W#16#0	
STATUS_SAV	Int	148.0	0	
SEND_REQ	Bool	150.0	FALSE	
SEND_DONE	Bool	150.1	FALSE	
SEND_BUSY	Bool	150.2	FALSE	
SEND_ERROR	Bool	150.3	FALSE	
SEND_REQ_P	Bool	150.4	FALSE	
SEND_REQ_I	Bool	150.5	FALSE	
SEND_STATUS	Word	152.0	W#16#0	
RECV_NDR	Bool	154.0	FALSE	
RECV_BUSY	Bool	154.1	FALSE	
RECV_ERROR	Bool	154.2	FALSE	
RECV_STATUS	Word	156.0	W#16#0	
RECV_LEN	Int	158.0	0	
RECV_LEN_S	Int	160.0	0	
ABORT_REQ	Bool	162.0	FALSE	
ABORT_DONE	Bool	162.1	FALSE	
ABORT_BUSY	Bool	162.2	FALSE	
ABORT_ERROR	Bool	162.3	FALSE	
ABORT_REQ_I	Bool	162.4	FALSE	
ABORT_REQ_P	Bool	162.5	FALSE	
ABORT_STATUS	Word	164.0	W#16#0	
STAT0	Bool	166.0	FALSE	
SEND_DATA	Array [1..50] Of Byte	168.0		

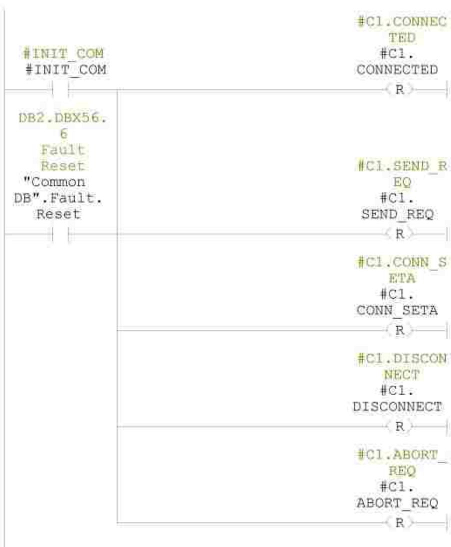
Name	Data Type	Address	Initial Value	Comment
RECV_DATA	Array [1..50] Of Byte	218.0		
TEMP		0.0		

Block: FB97

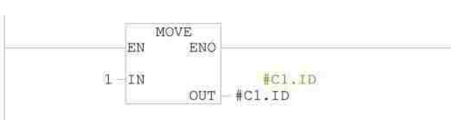
Note: TCP provides a reliable connection oriented end-to-end transport service based on a data stream on top of an unreliable network service. It manages end-to-end control and error checking to ensure complete data transfer.

Furthermore, TCP provides functions such as Sequencing, Flow Control and Error detection and Recovery.

Network: 1 Clear Bits to start initial connection and communication



Network: 2 Set individual local connection ID for all following functions



Network: 3 Set local TCP endpoint values:

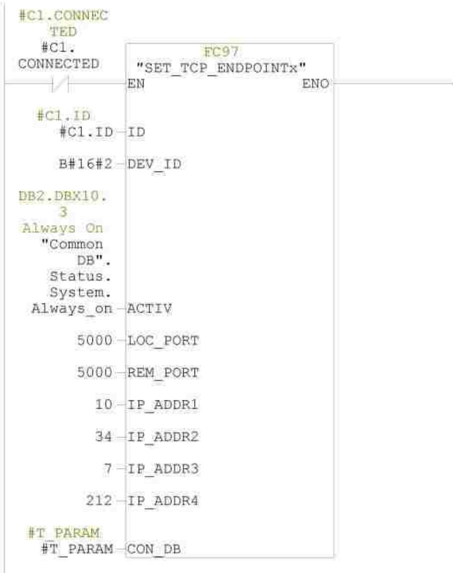
1) Parameter ID references the local ID of the connection.

2) The parameter DEV_ID assigns the Ethernet interface being used:
- "DEV_ID=B#16#2" for the CPU31x-2PN/DP or
- "DEV_ID=B#16#3" for the CPU319-3PN/DP or
- "DEV_ID=B#16#5" for the CPU41x-3PN/DP

```
3) The parameter ACTIVE determines the type of connection establishment:
   - FALSE: passive establishment
   - TRUE:  active establishment

4) The parameter LOC_PORT/REM_PORT assigns the local/remote port numbers.
   - if ACTIV=TRUE, remote port is mandatory (i.e., local port is irrelevant)
   - if ACTIV=FALSE, local port is mandatory (i.e., remote port is irrelevant)

5) The parameter IP_ADDR1 .. IP_ADDR4 identifies the remote IP address.
```

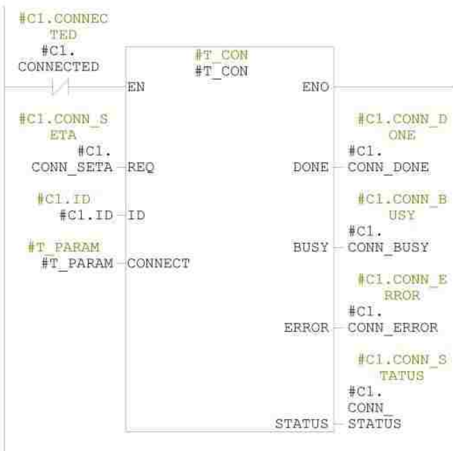


Network: 4 Establish TCP connection:

After the connection has been established, it is automatically monitored and maintained by the operating system of the CPU.

If the connection has been interrupted, by any line break or due to the remote communications partner, the active partner attempts to reestablish the connection.

Therefore, the FB 65 "TCON" may not be called again.



Network: 5 Create raising edge for the FB65 "TCON" ...

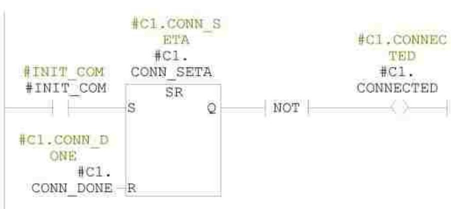
to set up the TCP connection (OB100 initial)!

Indication of the connection status:

a) If the CPU may establish the specified connection after Stop/Run immediately, the variable "CONNECTED" indicates HIGH (=1).

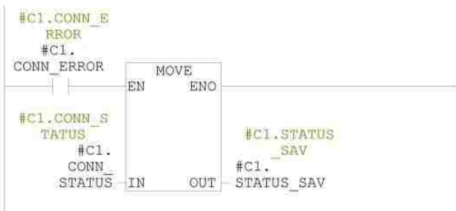
b) If the CPU is not able to establish the specified connection after Stop/Run, the variable "CONNECTED" remains LOW(=0).

c) Note: If the instance DB is loaded by the user, the variable "CONNECTED" indicates HIGH, although the connection may not be established yet. However, the FB64 "TRCV" would indicate the STATUS=0x80C4, as long as the connection has not been established.



Network: 6   Evaluate STATUS information ...

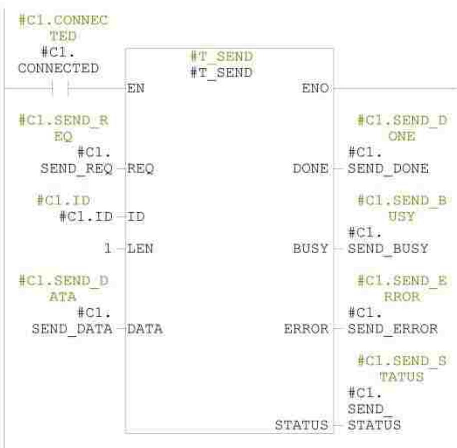
and save STATUS if ERROR has been occured!



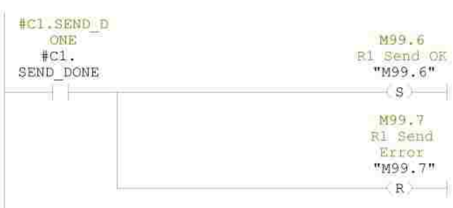
Network: 7   Invokes T_SEND function ...

if connection is established to transmit the data to the partner as a continues streams of bytes.

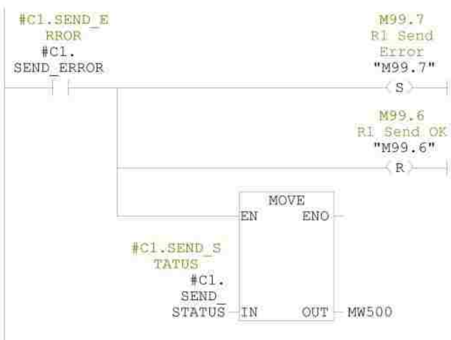
Note: Modify DATA and LEN parameter to your individual sending range!



Network: 8   Send OK

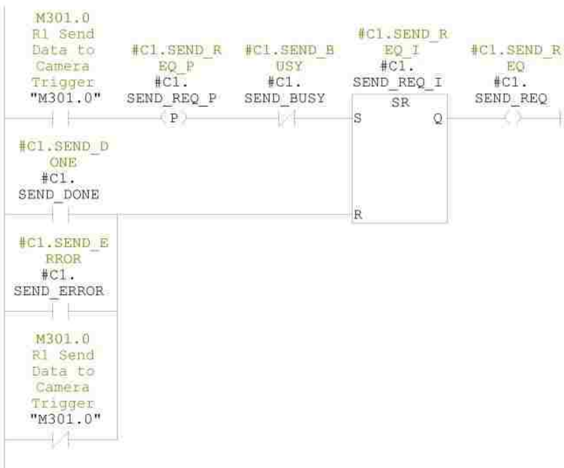


Network: 9 Send Error



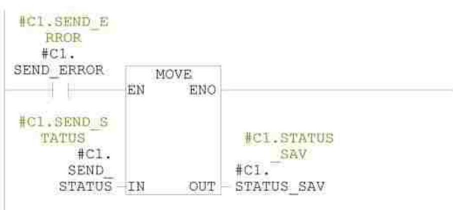
Network: 10 Send Data to Camera

Network: 11 Generate the rising edge SEND_REQ to start the T_SEND function



Network: 12 Evaluate STATUS information ...

and save STATUS if an ERROR has been occured!



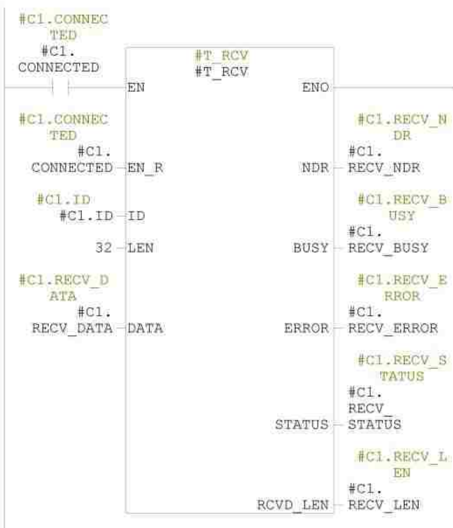
Network: 13 Enable T_RECV function

The data is stored into the buffer specified with the ANY pointer of the receive buffer (i.e., DATA parameter). After the data has been received, the data is immediately available in the receive buffer. Receiving is indicated by the NDR output parameter.

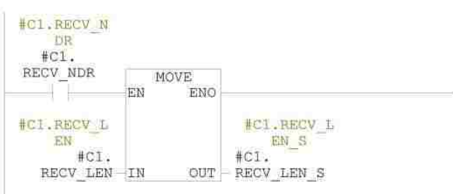
Mode LEN=0: The amount of data received is indicated within the RCVD_LEN parameter. The data can not be greater than the size specified in the DATA parameter.

Mode LEN=x: The data is stored into a buffer whose length is specified by the LEN parameter. If this specified length is reached, the received data is available in the DATA area. The RCVD_LEN signals identical amount of bytes specified by the LEN input parameter.

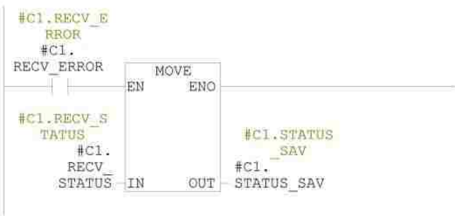
Note: Modify DATA and LEN parameter to your individual receiving range!



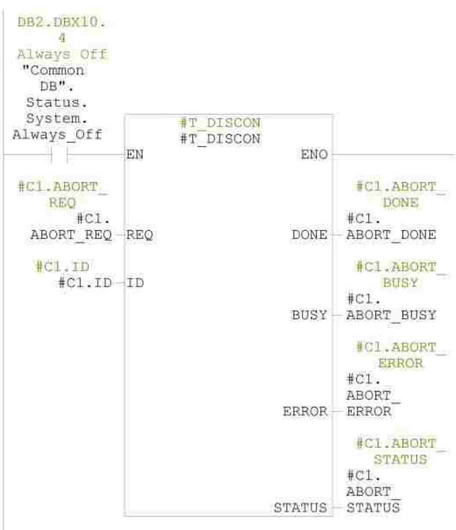
Network: 14 If new data available save the actual length of the data



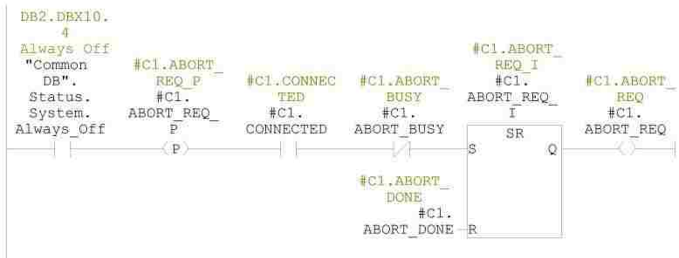
Network: 15 Evaluate STATUS information ...
and save STATUS if an ERROR has been occured!



Network: 16 Invoke T_DISC to abort TCP connection
The FB 66 "TDISCON" terminates a communications connection from the CPU to a communications partner. An existing connection is terminated when FB 66 "TDISCON" is called or when the CPU has gone into STOP mode. To reestablish the connection, the FB 65 "TCON" has to be invoked again. Note: Usually, that function must never be invoked. Therefore, this function remains disabled!



Network: 17 Generate the raising edge for T_DISC function block



Network: 18 Enable output ENO

VITA AUCTORIS

NAME:	Boris Novakovic
PLACE OF BIRTH:	Bosnia and Herzegovina
YEAR OF BIRTH:	1979
EDUCATION:	Mechanical Engineering Technology, St. Clair College, Windsor, ON, Canada, 2001
	Bachelor of Engineering Technology, University of Windsor, Windsor, ON, Canada, 2015