University of Northern Iowa

UNI ScholarWorks

Graduate Research Papers

Student Work

2016

Robotic High Precision Gaging Process

Andrew Leinen

Let us know how access to this document benefits you

Copyright ©2016 Andrew Leinen

Follow this and additional works at: https://scholarworks.uni.edu/grp

Offensive Materials Statement: Materials located in UNI ScholarWorks come from a broad range of sources and time periods. Some of these materials may contain offensive stereotypes, ideas, visuals, or language.

Robotic High Precision Gaging Process

Robotic High Precision Gaging Process

A Research Paper for Presentation
to the Graduate Faculty of
the Department of Technology
University of Northern Iowa

In Fulfillment of the Requirements for
The Non-Thesis Master of Science Degree

By
Andrew Leinen
June 19, 2016

This Study by: Andrew Leinen

Entitled: Robotic High Precision Gaging Process

Has been approved as meeting the research paper requirements for the

Degree of Master of Science – Industrial Management

6/24/2016

Date

Dr. Jin Zhu, Associate Professor – EET

6/20/2016

Date

Dr. Julie Zhang, Associate Professor – Manufacturing Technology

ABSTRACT

The following research paper describes a project that took place at a manufacturing company in the Spring of 2016. It involved integrating material handling robots into machining cells, which requires collaboration of many different departments and units within the company. The project was carried out from concept to completion including: working with project managers to conceptualize and finalize a robot cell layout, design and spec out grippers (end-of-arm-tooling), order all of the electrical components, create electrical schematics for the electricians, design safety circuitry, design and program Human Machine Interfaces (HMIs), Programmable Logic Controllers (PLCs), and program the robot. After the robot is running in production, support must be provided to each robot cell to prevent any unforeseen down-time.

The following research paper describes a project which determined that using a robot for in-process gaging can improve manufacturing part quality and alleviate ergonomic and safety concerns without sacrificing cycle time and part throughput.

INTRODUCTION

Industrial automation has advanced rapidly over the last ten years or more. Different machines, automated robots, and electrical sensors are changing the way that engineers solve complex problems, especially in the manufacturing industry. In order to stay competitive in the manufacturing market today, a company must meet product demand requirements otherwise they will not stay in business long. An increase in productivity can help a company raise their bottom line and stay competitive in the market. One approach to increasing productivity is by introducing and implementing the latest automation technologies and hardware. Robotic automation has become a very popular method of improving quality, efficiency, safety, and productivity in many different industries. According to the International Federation of Robotics, sales of industrial robots have risen 29% in 2014, with the worldwide total in 2014 reaching 230,000 units which is the highest level ever recorded for one year (Heer, 2016).

There are many industries that take advantage of robotic automation. Robots are being used in areas such as: food and beverage, medical device manufacturing, metals, pharmaceuticals, and automotive (Brown, 2008). Most robotic applications today are working in assembly type applications, putting pieces together. Other applications such as material handling, inspection, machine tending and palletizing are becoming more popular as companies see benefits such as repeatability, reliability, efficiency, and the increased flexibility in sophisticated robotic processes. Robots can work long hours in dirty environments that are not safe for human operators. This study discusses how the benefits of robotic automation helped improve multiple critical factors at a large manufacturing company.

The robotic integration group in which this study took place consists of two specialties, controls engineering and robot programming. The control engineers are in charge of the electrical schematics design, component selection, and safety circuitry while the robot programmer is responsible for writing the robot programs for each event that will occur (picking up part, setting down part, tending machines), step through the program and teach points using teach pendant controller for each part, and finally release the robot into production once fully programmed. Both of these specialties must work together and communicate effectively for a project to move forward and be completed on time. Several obstacles have been overcome when robot integration projects involve new or unique communication protocols that the group is not experienced with. The project in which this study took place includes one of these communication protocols, socket messaging via Ethernet IP. The author was the lead robot programmer for the project, responsible for creating the robot program, teaching points, training the operator and department manufacturing engineer, proving out the robot, and supporting production. More responsibilities include being in charge of the communication between the robot and high precision inspection gage, and between the robot and lathe CNC machine.

PURPOSE

Ergonomic concerns, safety concerns, and quality concerns were the main problems that were addressed in this research project. The answers are what the robotic integration group was responsible for - improve all of these concerns by integrating an automated robotic system. This specific robotic system did not replace a human operator, but improved their working environment by handling repetitive, monotonous tasks very easily and accurately. In order to meet the expectations and requirements of the customers, the manufacturing company must insure the highest quality products go out the door in into the final product. This can be achieved by very tight manufacturing tolerances, and frequent inspections taking place. The only way to insure there is 100% accuracy in this process is by using a robot. Using a robot will allow for no gaging errors as each part is inspected multiple times after different operations. This may not be an easy task for an operator because of many reasons. Humans are not perfect. When asked to repeat the same operation many times in a day, they can become less aware over time of their specific task, and that is when mistakes are made or nonconforming parts are produced. Also, having an operator physically remove a part from the machine and inspect after each operation is a huge cycle time and productivity loss, which must be avoided at all costs.

QUESTIONS TO BE ANSWERED

Throughout the course of this research project, the engineering team has been posed with several questions that need to be answered for justification of this automation project. The first obvious question was, "How can the quality of our product be improved?" The quality of the parts being manufactured has one of the largest impacts on a company. It affects not only the performance of the end product that the customer operates, but the reputation of that company and how they are perceived by customers, shareholders, and the media. Improving the quality of the final product means working from the ground up to introduce new technology and processes into the manufacturing of these parts.

The next question that had to be answered was, "Will automating the gaging process alleviate ergonomic concerns and alleviate other safety concerns?" Since this specific part is very heavy and difficult to maneuver, the manual gaging process was unsafe as far as ergonomic standards. An operator that runs this machining cell for eight hours will be exposed to heavy lifting, bending, and reaching inside the machine. Safety concerns such as the robot colliding with the operator must be addressed.

The final question that needed to be answered was, "Will using a robot to automate in-process gaging be a cycle time concern?" Each time a new machining operation or component (in this case a robot) is introduced in a work cell, cycle time concerns are raised. The team had to come up with a way to integrate in-process gaging with a robot, and not cut into the cycle time of the machining process.

LITERATURE REVIEW

The literature mainly consists of studies done with automated gaging processes, high speed Ethernet communication via socket messaging, various similar robotic application case studies, safety and ergonomic studies, as well as total quality management and lean manufacturing studies.

An article reviewed was written by Phillip Smith who is President and General Manager of Cincinnati Automation. He has been providing machine vision and laser gaging systems integration since 1993. This article gives really good insight on automated inspection and gaging systems, how they are used to help companies compete more effectively for new business, and other benefits that come with automated gaging in manufacturing. Smith discusses how properly designed and programmed in-process automated gaging can greatly improve product quality. Automated gaging, especially with a robot allows for very fast processes that are accurate and extremely repeatable.

An article reviewed was written by Bennett Brumson, Contributing Editor of RIA (Robotics Industries Association). RIA publishes Robotics Online which provides information to help engineers, managers and executives apply and justify robotics and flexible automation. Founded in 1974, RIA is the only trade group in North America organized specifically to serve the robotics industry. This article is a great source of information regarding how robotics can eliminate ergonomic hazards and other factors such as lower insurance premiums for manufacturers who implement robots, and for labor unions who really benefit from lower ergonomics risks. The article discusses many areas of opportunity for robotic integration to help with ergonomic risks, palletizing possibilities, as well as insurance incentives. Dan Harmon also discusses in a journal submission that robotic gaging and inspection ensures operator safety by allowing them to stay focused on the machining process, rather than the control system, and function as a more natural machine interface. Overall the less the operator has to handle the part, the more ergonomically safe the operation becomes. Ergonomic concerns are directly affected by the project in which this paper discusses.

An article reviewed was written by Tanya Anandan, Contributing Editor of RIA. This article delves into many different robotic safety aspects including OSHA (Occupational Safety and Health Administration) provisions, Lockout/Tagout Debates, Safe guarding robotic applications, and knowing the risk of implemented robotics in the workplace. This research paper is directly related to increasing safety by integrating a robotic gaging process.

A tutorial article does a great job of explaining a high up overview of PC sockets, also how to read and write to and from a socket. Socket messaging via Ethernet IP is the communication protocol required for this robotic application. A socket is one end-point of a two-way communication link between two programs running on the network according to The Java Tutorials. Oracle and Java have a known reputation of being industry leading with software development and communication. This robotic application requires socket messaging as the standard communication protocol between the gage and robot since the gage program will be running on an industrial PC connected to the network.

ONE Robotics was founded in early 2012 after Jay Strybis decided to leave FANUC Robotics to focus more on his web development company. Jay has done a lot of work with visual line tracking, PickTool, PalletTool, and KAREL programming. His website is a great source of information for an introduction to KAREL programming. KAREL is a lower-level language very similar to Pascal, and gives the robot programmer access to all sorts of useful built-ins for things the programmer cannot normally do with the robot's teach pendant. It turns out that KAREL programming was required in order to utilize Socket Messaging communication via Ethernet IP since this type of communication does not come standard on Fanuc robot controllers. This introduction was used to help me get a broad understanding of KAREL, and the basics of the programming structure. It was also a good reference for when we purchased the Fanuc robot as the website directly states, "As of the R-30iB controller you must have the KAREL software option in order to load your own custom KAREL programs". This KAREL option is not one of the standard options that we purchase on the robot, so we had to ensure this was ordered and came with the robot from the factory.

A textbook was reviewed which was purchased and used for coursework in the Masters of Technology curriculum. The Lean concepts and principles described in this book have revolutionized manufacturing practice and business conduct in a manner similar to what Henry Ford's system did for mass manufacturing. From fundamental concepts such as the 5S principle and 7 wastes in manufacturing, to integrated planning and control in pull production and the supply chain, this book provides a complete introduction to Lean production. Coverage includes small batch production, setup reduction, pull production, preventive maintenance, standard operations, as well as synchronizing and scheduling lean operations. These lean manufacturing concepts were used in this project to drive towards improving efficiency, productivity, and quality. Since every company wants to eliminate wastes or non-value added activities as much as possible, these wastes must be investigated and eliminated. I used the knowledge gained from this course, as well as the textbook to contribute directly in this automation cell's layout, and design for the operator and placement of electrical panels, gaging tools, and overhead hoists.

An article was reviewed covering the 7 Wastes in Manufacturing was retrieved from EMS Consulting Group's website. EMS Consulting Group, Inc. was founded in 2003 by Darren Dolcemascolo and David McBride. They have many years of experience with lean transformation, and together developed a Lean Certification program. EMS provides their clients with customized lean training, coaching, and facilitation support while helping them build the continuous improvement needed for running a lean company. The training programs that they offer are customized to each of their client's unique situations and business strategies. This article describes what the 7 Wastes consists of, and reasons why they should be eliminated from every company to improve key aspects of business. Several of these 7 wastes were eliminated as this research project took place, and these will be highlighted during the analysis section of the paper.

This article was reviewed to discover all of the different ways of gaging parts in a manufacturing facility today. The BNP Media Staff which includes, Javier Guerra and Daryle Higginbotham, have signed a strategic agreement of collaboration to develop a wide range of NDT services and products to position themselves within the top-ranking companies in the U.S. within the composites inspection area. This article provides a great overview of automated gaging systems, and how they can provide advantages over manual gaging systems. It also describes the system components that must be in place for automated gaging, different choices in gaging technology, and how to get the most value out of different gaging processes such as properly allocated floor space and coordination of downstream processes.

An article was used to research common gage calibration practices, reasons to calibrate, calibration frequency, as well as developing a calibration frequency process. The BNP Media Staff which includes, Javier Guerra and Daryle Higginbotham, have signed a strategic agreement of collaboration to develop a wide range of NDT services and products to position themselves within the top-ranking companies in the U.S. within the composites inspection area. This article provided great information that relates to this project because calibration of the high precision gage is required for accurate measurements. The team was unsure of many of the factors about calibration which this article describes in good detail such as developing a calibration frequency process, and how often we should calibrate the gage.

An article was reviewed that discusses Six Sigma in great detail, explaining the importance to every company in many different industries. Harry and Schroeder explain, "Six Sigma is a business process that allows companies to drastically improve their bottom line by designing and monitoring everyday business activities in ways that minimize waste and resources while increasing customer satisfaction". From this definition it is easy to understand Six Sigma and how it can be applied at the workplace in different industries. Defects and waste happen at almost every company, but minimizing these defects will drastically improve the company's revenue while reducing lost time, material, and possibly the workforce. This project team took in consideration Six Sigma quality standards and strived for this when answering questions regarding part quality for manufacturing. The team knew that without striving for Six Sigma, customers would not buy the product, and our competitors would take over the market.

RESEARCH METHOD

The research process with for this project took place over several months and included finding information from many different sources, running computer simulations, and testing Ethernet communication protocols. One of the most important factors of this project was if the automated gaging with a robot is feasible enough to implement. Smith, P wrote a great article titled: Automated Inspection & Gaging Systems Improve Quality and Reduce Costs that hits on several key areas including how these systems can improve product quality, grow a business, reduce manufacturing costs, different types of automated inspection and gaging systems, as well as how to select a supplier. He describes, "Automated Inspection & Gaging Systems can help companies to improve overall product quality and grow their business while reducing manufacturing costs, helping them to become more competitive in this difficult business climate." The information that Smith provides in this article helped justify the need for an automated gaging process. It has many advantages over the manual gaging that is taking place today including: improved accuracy, no ergonomic concerns, improved efficiency, and longevity of operation. Companies can monitor the inspection results data and then immediately correct process problems that cause rejects therefore reducing scrap and improving line efficiency (Smith, 2009).

Ergonomics are one of the biggest safety concerns in manufacturing factories today. Since the components that are being manufactured in this study are very large and heavy, ergonomics were highly stressed. Research had to be conducted to ensure these safety concerns were eliminated, and Bennett Brumson, Contributing Editor of RIA wrote a great article regarding ergonomics and how robots can be implemented to help with these safety concerns. RIA publishes Robotics Online which provides information to help engineers, managers and executives apply and justify robotics and flexible automation. Bennett quotes Alan Hedge, a professor of ergonomics at Cornell University, "Workers are being injured by lifting heavy objects. If a robotic device can be used to do the heavy lifting that would be wonderful." Hedge also notes the ergonomic risks of working overhead, a common practice in automobile manufacturing. "Anyone who has to work with their arms above elbow level is going to experience an increase in shoulder-loading, which is going to translate into an increased risk of injury. If you can design a robot to perform that kind of function that would be ideal." In the case of this research project, the robot was not used for maneuvering the heavy parts. Instead this was automated by the Lathe CNC machine, and a cradle operation. Instead of the operator leaning, and bending inside the machine to load the part into the chuck, the operator will place the part on a cradle which is presented to the door by the lower cutting spindle. This cradle will load as well as unload the part from the chuck for the operator.

Where the robot plays a major ergonomic alleviator is in the gaging process. These parts are held to such tight tolerances that 100% inspection/gaging is required. In order for this to happen, the operator has to manually unload the part from the chuck, and place it on a gaging stand. He then has to use a snap gage to inspect different journals and features of this part, which takes upwards of five minutes. After gaging, he determines if offsets or adjustments need to be made inside the CNC machine for the next part. In the new automated in-process gaging operation, the machine will perform its operation, and then signal the robot to gage the part. The robot will enter the machine promptly from the top-side, gage the part, and return to its home position. The instant the robot is done gaging the part, the discrepancies or differences between the machined part and the tolerance print are sent directly to the Lathe CNC machine. These numbers are then used for offsetting cutting tools for the next part. Having this gaging operation in-process allows for much more accurate machining, gaging accuracy, efficient operations, improved part quality, as well as eliminating the huge ergonomic hazard of having an operator gage this part manually.

One of the fastest and most efficient ways to increase quality and improve efficiency of an operation is by eliminating non-value added activities, known as wastes. There are many lean manufacturing principles that exist, but one of the most popular today is Toyota's Seven Wastes. These seven wastes include: Overproduction, Waiting, Transporting, Inappropriate Processing, Unnecessary Inventory, Excess Motion, and Defects (McBride, 2003). Two of these wastes that are directly eliminated in this project are Excess Motion, and Defects.

Excess Motion occurs when ergonomic hazards (bending, reaching, walking, lifting, stretching) are present, which can introduce health and safety issues as previously mentioned. The non-value activity of excess motion was eliminated by introducing automated in-process gaging with a robot, as well as automated part loading and unloading with the CNC machine turret cradle. Now the operator will no longer have to reach inside the machine to maneuver the part, lift it into position, and stretch to load it correctly.

Defect waste directly impacts the company's bottom line by creating costs due to rework scrap and loss of customers. David McBride explains, "Associated costs include quarantining inventory, re-inspecting, rescheduling, and capacity loss. In many organizations the total cost of defects is often a significant percentage of total manufacturing cost". The waste of Defects was eliminated by the high precision gaging performed by the robot. This gaging process will detect any nonconformities at the earliest point in the process. Any deviations from the part schematic would cause the gage to send offset values to the CNC machine, which will compensate for those differences and produce a good part.

In order to perform this automated high precision gaging using a robot, significant research had to be conducted over the socket messaging communication protocol, and KAREL robot programming. According to Java Tutorials, "A socket is a one end-point of a two-way communication link between two programs running on the network". In the case of this project, one program is running on the robot which is the "client", while the other is running on the industrial PC, the "server", for the high precision gage. They are connected via an Ethernet cable, and therefore have the possibility to read and write messages to a socket of other devices. The industrial PC, which is the server, has a socket that is bound to a specific port number. The server just waits, listening to the socket for a client to make a connection request. The client knows the hostname (IP address) of the machine on which the server is running and the port number on which the server is listening. To make a connection request, the client tries to rendezvous with the server on the server's machine hostname and port. If everything goes well, the server accepts the connection. On the client side, if the connection is accepted, a socket is successfully created and the client can use the socket to communicate with the server. The client and server can now communicate by writing to or reading from their sockets (Java Tutorials). The robot and PC are sending string data types back and forth to determine when to start the gaging process, end the gaging process, and other feedback such as failed calibration or successful calibration.

In order to utilize socket messaging communication within the robot, KAREL programming must be used. All Fanuc robots run KAREL as the backbone of their programming environment. Normally creating these programs are avoided because of the complexity, but in this project it was required. A special license was purchased to be able to created KAREL programs, and extensive research was completed. This included reading Jay Strybis' article "Introduction to KAREL Programming". Here he discussed a summary of KAREL, and some example code that really helped develop the code for this project. Though KAREL is a complex language, the program for this project was kept brief, and only needed the ability to establish communication to the PC's socket, and send and receive strings accordingly.

An obstacle that had to be overcome involved calibrating the high precision gage, and determining the frequency at which to calibrate this. A master disc with known dimensions was provided by the gage vendor. This is what the gage will scan in order to determine accuracy and if the gage lasers need cleaning or maintenance. This master disc was mounted on top of the CNC machine, next to the robot so that calibration could be performed easily and efficiently. BNP Media Staff's article "The Importance of Scheduling Calibration" was directly referenced when determining common gage calibration practices, reasons to calibrate, calibration frequency, as well as developing a calibration frequency process. Their definition of calibration is, "Calibration is the process of determining the numerical relationship between observed output of a measurement system and the value of the characteristic being measured based on reference standards". In the case of this project, the master disc's dimensions are the known standard. The team learned that simple things such as temperature swings, dust, and humidity can cause the gage to misread, or provide bad results thus requiring calibration. Since this gage measuring device is very important to our manufacturing process, we decided to calibrate it every five parts. The robot program is incrementing a register, and before the gaging process on the fifth part, a calibration sequence will run. This ensures that we are collecting the most accurate data from the gage, and no outside factors are causing misreads leading to nonconforming products. Of course if more frequent calibration is needed, the robot can be adjusted for this easily.

PROJECT WORK

1) Conduct research to provide answers to project managers as far as feasibility and if this process has the capability to improve part quality.
2) Create simulation of robot cell in Fanuc provided computer software to prove out robot program, KAREL program, and socket messaging concepts.
3) After robot was installed and powered, download entire work cell from Fanuc software to actual robot.
4) Test communication between robot, lathe CNC machine, and high precision gage.
5) Pick robot points above machine, inside machine, and for gaging the parts.
6) Perform tests to provide data for accuracy of high precision gage.
7) Record results in table, and provide these to project managers.
8) Prove out calibration process of the high precision gage.

9) Train operators on how to cycle start robot, machine, recover from faults, and show them how ergonomic concerns have been eliminated.

10) Release to production, and support while robot is running.

DATA ANALYSIS

Data has been collected over a series of 41 trial runs and prove outs with the robot, high precision gage, and CNC machine. Eleven of these runs were conducted at 50% max speed of the robot, twenty runs were conducted at 100% max speed of the robot, and ten of these runs were conducted at 100% max speed of the robot, with the gage angled 155°. These different tests were conducted by the team to ensure accuracy, and repeatability, as well as the best method for gaging. Also the gage is measuring the diameter at six different critical features of the part in millimeters.

Table 1. Measurement Deviations at 50% Robot Speed

50% Robot Speed													
Date	Run		mm		mm		mm		mm		mm		mm
4/6/2016 18:52	1	Diameter 1	59.9676	Diameter 2	58.4442	Diameter 3	58.4715	Diameter 4	65.827	Diameter 5	58.4233	Diameter 6	65.8257
4/6/2016 18:52	2	Diameter 1	59.9679	Diameter 2	58.4446	Diameter 3	58.4717	Diameter 4	65.8277	Diameter 5	58.4225	Diameter 6	65.825
4/6/2016 18:52	3	Diameter 1	59.9666	Diameter 2	58.4443	Diameter 3	58.4711	Diameter 4	65.8288	Diameter 5	58.4224	Diameter 6	65.8262
4/6/2016 18:53	4	Diameter 1	59.9679	Diameter 2	58.4435	Diameter 3	58.4709	Diameter 4	65.8284	Diameter 5	58.422	Diameter 6	65.8257
4/6/2016 18:53	5	Diameter 1	59.9674	Diameter 2	58.444	Diameter 3	58.472	Diameter 4	65.8272	Diameter 5	58.4232	Diameter 6	65.825
4/6/2016 18:53	6	Diameter 1	59.9682	Diameter 2	58.444	Diameter 3	58.471	Diameter 4	65.8272	Diameter 5	58.4227	Diameter 6	65.826
4/6/2016 18:54	7	Diameter 1	59.9664	Diameter 2	58.4439	Diameter 3	58.4717	Diameter 4	65.8279	Diameter 5	58.4227	Diameter 6	65.8261
4/6/2016 18:54	8	Diameter 1	59.9678	Diameter 2	58.4439	Diameter 3	58.4718	Diameter 4	65.8286	Diameter 5	58.4228	Diameter 6	65.8254
4/6/2016 18:54	9	Diameter 1	59.9669	Diameter 2	58.4444	Diameter 3	58.4704	Diameter 4	65.8279	Diameter 5	58.4235	Diameter 6	65.8258
4/6/2016 18:54	10	Diameter 1	59.9672	Diameter 2	58.4447	Diameter 3	58.4711	Diameter 4	65.8276	Diameter 5	58.4225	Diameter 6	65.8255
4/6/2016 18:55	11	Diameter 1	59.9679	Diameter 2	58.4435	Diameter 3	58.4711	Diameter 4	65.8277	Diameter 5	58.4217	Diameter 6	65.8254
Average			59.9674		58.4441		58.4713		65.8278		58.4227		65.8256
Min			59.9664		58.4435		58.4704		65.8270		58.4217		65.8250
Max			59.9682		58.4447		58.4720		65.8288		58.4235		65.8262
Std Dev			0.0006		0.0004		0.0005		0.0006		0.0005		0.0004
Max Dev			0.0018		0.0012		0.0016		0.0018		0.0018		0.0012

Table 1 displays the first trials with the robot at 50% speed. These trials showed maximum deviations in measurements of 1.8 µm, 1.2 µm, 1.6 µm, 1.8 µm, 1.8 µm, and 1.2 µm. The average of these maximum deviations equals 1.6 µm. These results were a very good and impressive start, well within the acceptable accuracy of the gage and inspection process. With results this good, the team was able to test the gage with the robot running at full speed, simulating the speed it would run at during production.

Next were the twenty runs at 100% robot speed in Table 2.

Table 2. Measurement Deviations at 100% Robot Speed

100% Robot Speed													
Date	Run		mm		mm		mm		mm		mm		mm
4/6/2016 19:58	12	Diameter 1	59.9671	Diameter 2	58.4441	Diameter 3	58.472	Diameter 4	65.8269	Diameter 5	58.4239	Diameter 6	65.8233
4/6/2016 19:58	13	Diameter 1	59.9683	Diameter 2	58.4437	Diameter 3	58.4723	Diameter 4	65.8281	Diameter 5	58.4228	Diameter 6	65.8229
4/6/2016 19:58	14	Diameter 1	59.9674	Diameter 2	58.4438	Diameter 3	58.4717	Diameter 4	65.8277	Diameter 5	58.4231	Diameter 6	65.8232
4/6/2016 19:59	15	Diameter 1	59.9672	Diameter 2	58.4444	Diameter 3	58.4726	Diameter 4	65.828	Diameter 5	58.4244	Diameter 6	65.8232
4/6/2016 19:59	16	Diameter 1	59.967	Diameter 2	58.4436	Diameter 3	58.472	Diameter 4	65.829	Diameter 5	58.424	Diameter 6	65.8233
4/6/2016 19:59	17	Diameter 1	59.9667	Diameter 2	58.4437	Diameter 3	58.4725	Diameter 4	65.8282	Diameter 5	58.4243	Diameter 6	65.8237
4/6/2016 19:59	18	Diameter 1	59.9672	Diameter 2	58.4435	Diameter 3	58.4721	Diameter 4	65.8281	Diameter 5	58.4231	Diameter 6	65.8236
4/6/2016 20:00	19	Diameter 1	59.9674	Diameter 2	58.4438	Diameter 3	58.472	Diameter 4	65.8287	Diameter 5	58.4236	Diameter 6	65.8236
4/6/2016 20:00	20	Diameter 1	59.9673	Diameter 2	58.4434	Diameter 3	58.4719	Diameter 4	65.828	Diameter 5	58.4241	Diameter 6	65.8235
4/6/2016 20:00	21	Diameter 1	59.9676	Diameter 2	58.4442	Diameter 3	58.4719	Diameter 4	65.8277	Diameter 5	58.4236	Diameter 6	65.8236
4/6/2016 20:00	22	Diameter 1	59.9671	Diameter 2	58.4441	Diameter 3	58.4724	Diameter 4	65.8275	Diameter 5	58.4225	Diameter 6	65.8236
4/6/2016 20:00	23	Diameter 1	59.9668	Diameter 2	58.4439	Diameter 3	58.4722	Diameter 4	65.8287	Diameter 5	58.4242	Diameter 6	65.8238
4/6/2016 20:01	24	Diameter 1	59.9677	Diameter 2	58.444	Diameter 3	58.472	Diameter 4	65.8286	Diameter 5	58.4238	Diameter 6	65.8238
4/6/2016 20:01	25	Diameter 1	59.9664	Diameter 2	58.4439	Diameter 3	58.4728	Diameter 4	65.8291	Diameter 5	58.4227	Diameter 6	65.8237
4/6/2016 20:01	26	Diameter 1	59.9663	Diameter 2	58.4441	Diameter 3	58.4725	Diameter 4	65.8276	Diameter 5	58.4229	Diameter 6	65.8237
4/6/2016 20:01	27	Diameter 1	59.9672	Diameter 2	58.4444	Diameter 3	58.4719	Diameter 4	65.8274	Diameter 5	58.4233	Diameter 6	65.8236
4/6/2016 20:02	28	Diameter 1	59.9674	Diameter 2	58.4442	Diameter 3	58.4728	Diameter 4	65.8274	Diameter 5	58.4231	Diameter 6	65.8235
4/6/2016 20:02	29	Diameter 1	59.9676	Diameter 2	58.4435	Diameter 3	58.4724	Diameter 4	65.8271	Diameter 5	58.4234	Diameter 6	65.8236
4/6/2016 20:02	30	Diameter 1	59.9669	Diameter 2	58.4435	Diameter 3	58.4718	Diameter 4	65.8279	Diameter 5	58.4233	Diameter 6	65.8237
4/6/2016 20:02	31	Diameter 1	59.967	Diameter 2	58.4436	Diameter 3	58.4718	Diameter 4	65.8284	Diameter 5	58.4238	Diameter 6	65.8235
Average			59.9672		58.4439		58.4722		65.8280		58.4235		65.8235
Min			59.9663		58.4434		58.4717		65.8269		58.4225		65.8229
Max			59.9683		58.4444		58.4728		65.8291		58.4244		65.8238
Std Dev			0.0005		0.0003		0.0003		0.0006		0.0006		0.0002
Max Dev			0.0020		0.0010		0.0011		0.0022		0.0019		0.0009

With running the robot at 100% full speed, the maximum deviations recorded were: 2.0 µm, 1.0 µm, 1.1 µm, 2.2 µm, 1.9 µm, and 0.09 µm. The average maximum deviation for running at 100% speed equals 1.5 µm. This averaged turned out to be less than when running at 50% speed! It was originally believed that the slower the speed of gaging, the more accurate and repeatable the gage would be, but this does not seem to be the case. This was great news because now the team knew they could run the robot at 100% speed during production hours. This means reduced cycle time and increased productivity.

After running several cycles in-process with the CNC machine, it was noted by a team member that one of the turrets inside the machine might be an issue. When it is extended all the way forward, it has the cutting tools and part cradle embedded into it. This might cause the robot to collide with it as it enters the machine to gage the part. The team then came up with the solution of rotating the robot and gage 155° so that it would miss this lower turret of the CNC machine, and also may create more accurate readings as coolant does not tend to collect on the sides of the part, mostly on the bottom and top. This coolant collecting could cause the gage to provide inaccurate data, and then the machine may produce nonconforming parts.

Table 3. Measurement Deviations at 100% Robot Speed, Rotate 155°

100% Robot Speed, Rotated 155°													
Date	Run		mm		mm		mm		mm		mm		mm
4/6/2016 20:04	32	Diameter 1	59.9729	Diameter 2	58.4367	Diameter 3	58.4656	Diameter 4	65.8243	Diameter 5	58.4246	Diameter 6	65.8216
4/6/2016 20:04	33	Diameter 1	59.9726	Diameter 2	58.4371	Diameter 3	58.4651	Diameter 4	65.8245	Diameter 5	58.4255	Diameter 6	65.8216
4/6/2016 20:04	34	Diameter 1	59.9724	Diameter 2	58.4367	Diameter 3	58.4654	Diameter 4	65.8248	Diameter 5	58.4256	Diameter 6	65.8211
4/6/2016 20:04	35	Diameter 1	59.9723	Diameter 2	58.4371	Diameter 3	58.4653	Diameter 4	65.8246	Diameter 5	58.4251	Diameter 6	65.8211
4/6/2016 20:05	36	Diameter 1	59.9728	Diameter 2	58.4364	Diameter 3	58.4654	Diameter 4	65.8245	Diameter 5	58.4255	Diameter 6	65.8212
4/6/2016 20:05	37	Diameter 1	59.9726	Diameter 2	58.4371	Diameter 3	58.4646	Diameter 4	65.8245	Diameter 5	58.4258	Diameter 6	65.8211
4/6/2016 20:05	38	Diameter 1	59.9726	Diameter 2	58.4366	Diameter 3	58.4654	Diameter 4	65.8247	Diameter 5	58.4253	Diameter 6	65.8212
4/6/2016 20:05	39	Diameter 1	59.9724	Diameter 2	58.4369	Diameter 3	58.4647	Diameter 4	65.8247	Diameter 5	58.4264	Diameter 6	65.8215
4/6/2016 20:06	40	Diameter 1	59.9722	Diameter 2	58.4373	Diameter 3	58.4653	Diameter 4	65.8247	Diameter 5	58.4249	Diameter 6	65.8212
4/6/2016 20:06	41	Diameter 1	59.9727	Diameter 2	58.4373	Diameter 3	58.4653	Diameter 4	65.8246	Diameter 5	58.4252	Diameter 6	65.8212
Average			59.9726		58.4369		58.4652		65.8246		58.4254		65.8213
Min			59.9722		58.4364		58.4646		65.8243		58.4246		65.8211
Max			59.9729		58.4373		58.4656		65.8248		58.4264		65.8216
Std Dev			0.0002		0.0003		0.0003		0.0001		0.0005		0.0002
Max Dev			0.0007		0.0009		0.0010		0.0005		0.0018		0.0005

After rotating the robot 155°, the maximum deviations for each of the six critical diameters were: 0.07 µm, 0.09 µm, 1.0 µm, 0.05 µm, 1.8 µm, and 0.05 µm. The team was very happy to see the average reduced to only 0.009 µm. This gave the team confidence that when rotated at 155° the robot would not collide with the lower turret, gage very accurately, and also run at 100% of the robot's full speed.

CONCLUSION

Overall this robotic high precision gaging project broke a lot of new ground for the robotic integration team. It required researching several new technologies, safety regulations and standards, as well as best practices and feasibility information. The main three questions of how we can improve the quality of our product, alleviate ergonomic and safety concerns, and not increase machining cycle times were directly answered in the research provided. Product quality will be improved by implementing this high precision gage due to the fact that 100% of the parts are checked for nonconformance, and the CNC machine is applying offsets to improve product quality in-process. Ergonomic and safety concerns were eliminated by automating a part cradle system in the CNC machine to load and unload these heavy parts for the operator, eliminating the process for the operator to have to gage these parts manually outside of the machine, and integrating safety area scanners to prevent the robot from colliding into obstacles or possibly a human. These operations with the robot were integrated without sacrificing cycle time.

In the future, automating high precision gages will be very beneficial for manufacturing factories, and manufacturing companies worldwide. It takes out the process error due to a human operator, and can provide very accurate results as shown in this research paper. Safety and ergonomic concerns are also greatly reduced or eliminated which helps justify this type of automated gaging. Future studies should include integrating a robot that performs the material handling, as well as the high precision gaging. That would eliminate the need for an operator to intervene with the machining process, and further improve cycle times and productivity.

The technologies used in this project such as Socket Messaging and KAREL programming will help this robotic integration team develop future projects, and utilize these technologies to incorporate more innovative processes and operations. Using these technologies will open doors to new ideas and enhanced automation that will help improve product quality and productivity levels.