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ROBOTIC AUTOMATION OF A CNC MACHINE

by

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A thesis submitted in partial fulfillment of the requirements
for the Honors in the Major Program in Mechanical Engineering
in the College of Engineering and Computer Science
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at the University of Central Florida
Orlando, Florida

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Thesis Chair: Dr. Dazhong Wu

Abstract

Robotic automation of CNC machines is becoming more popular as robot technology advances and becomes more readily available. While some CNC machines can run autonomously with part catchers, vertical milling centers require an external entity to keep the machine running. Collaborative and Industrial robots are the two main selections for automating a vertical CNC milling machine. We investigate specifically which robot type is most effective for machine tending a Haas VF2 vertical milling center. To do this a cell floorplan, risk assessment, overall equipment effectiveness evaluation, and a total cost analysis are performed to compare robots. With this results of each analysis process, it appears the industrial robot is most effective for the machine tending case.

Dedication

This work is dedicated to Bodi Cartmill Hovey, friend, family member and mentor.

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Introduction

In the modern age of industrial manufacturing, advanced software and hardware direct conversation toward robotic automation. Robotic automation is taking a current process performed by a human and reconfiguring it for a robot to complete. This automation also includes beginning design of a manufacturing process with full automation in mind. There are two main types of robots to address. The first, an industrial robot, as defined by Robotic Industries Association (RIA) is “a reprogrammable, multifunctional manipulator designed to move material, parts or special devices through variable programmed motions for the performance of a variety of tasks” [2]. Fundamentally, the industrial robot is not a new advancement. Industrial robots are composed of a controller, a power supply box and the robot. Inside the robot is typically 6 finely controlled electric motors. The automobile industry was the first to implement robots based on this definition into their production line. The first installment of an industrial robotic arm took place in Ternstedt, New Jersey, at the General Motors plant in 1963 [3]. Over the last 50 years, robots have been used to automate large scale manufacturing primary in the automotive and electronics. In 2010, the second form of robotic was introduced to the manufacturing industry. Universal Robotics created the first collaborative robot [4]. Once again, the automobile industry found swift use of the new technology. The RIA describes a collaborative robot as “a robot specifically designed for direct interaction within a defined collaborative workspace” [2]. Collaborative robots can work within reach of a human enlarging their potential workspace compared to industrial robot requiring safety fencing. Examples of collaborative workspaces include assembly lines, pick and place, and machine tending.

There is a gap in research regarding a standard process to objectively select the best type of robot to perform each job most effectively. We will be looking specifically into CNC manufacturing. Since CNC manufacturing is considered to be a vertebra in the spine of industrial manufacturing, it is important to identify the most effective way to automate these machines for efficiently. Introducing two types of solutions for automating CNC machine tending, this paper will outline the process to reach a reliable solution for determining the type of robot most effective. Defining the hypothesis as “if a company desires to automate a CNC machining cell, then the best way is to use an industrial robot as opposed to collaborative.” To evaluate the hypothesis, a standard process will be created to quantify significant factors of a machine tending cell. Furthermore, these factors will be analyzed with industry efficiency and productivity standards detailed in the literature review and methodology.

Literature Review

With the current robotic technology, it is possible to automate approximately 60% of CNC machine tending labor input [4]. The incentive to increase automation is an increase in productivity and quality within the machining process while reducing cost. In a research study looking at a sheet metal press line, cost was reduced by 50% while productivity was increased by 30% and utilization by 85% [11]. Research literature suggests there is not a question of whether automation will improve a machining operation that currently requires repetitive human input. The vacancy of literature arises when selecting the ideal way to automate a machine tending process with the current technology and a corresponding decision-making methodology. Scant metrics compare the effectiveness and productivity levels of a collaborative vs industrial robot. However, there are several metrics that have been created to look at efficiency and productivity in manufacturing plants.

There are several forms to create metrics of production. This paper will focus on two, evaluating effectiveness and productivity. The first, Asset Utilization (AU) is "the ratio of actual output that could be achieved if a plant ran at maximum capacity for 365 days a year while producing 100% quality product" [5]. The second form, Overall Equipment Effectiveness (OEE) is used in lean manufacturing to look at the availability, performance and quality [7]. [10] demonstrates the use of OEE to quantify the changes to improve the efficiency of a stamping press. OEE showed a 55% increase after the lean manufacturing and TPM changes were made. Effectiveness of equipment such as a CNC machines is derived from the lean analysis of performance and quality. Further, this information is concluded as a percentage increase in OEE. The research from [6] and [7] discusses the ability to calculate metrics on the productivity and efficiency of a manufacturing process, however it does not speak directly about the use of collaborative versus industrial robots.

[8] Discusses the capability of industrial robots to automate applications such as machine tending, painting and assembly. Further it discusses controls and feedback, as well as how advanced technology ensures reliability of industrial robots. This literature is very technical on the mechanics of robotic arms. However, it does not discuss the barrier of integration for industrial arms, including safety fencing and risk assessment. Furthermore, [8] does not provide an OEE or AU evaluation detailing how an industrial robot impacted performance or quality, adding value as an automation tool.

Methodology

The methods that will be used throughout the process include several steps. The first step will be to define the scope of a CNC machine tending cell for this research. The second step will be the setup of two separate cells designed to meet industry specifications for safety while satisfying functional machine tending requirements. The third step will involve the evaluation of throughput within the specified cell using the OEE model. The fourth step will be calculating the costs associated with each cell. Finally, the information from each evaluation model will be integrated into an overall evaluation calculation resulting in a value for each cell to determine the most efficient robotic system. After further consideration, the OEE model is determined to encompass asset utilization in the subsection of availability. Although asset utilization goes into cost and would show difference between robot and human machine tending most effectively. For this robot to robot comparison, OEE and the other steps in the methodology will be adequate to determine which robot is more effective.

First, the cell contains one CNC machine, a Haas VF2-SS. This is a vertical mill readily available in the geographic region of research. Additionally, the cell will contain a raw material region the robot will use to pick up material to load the machine. Post machining, a CMM will be utilized to validate machined dimensions. After the CMM inspection, the robot will place the complete part in either a pass or fail region. The last item in the cell is the robot. This will be the only functional difference between each of the two cells. The core components including the Haas VF2, CMM and part storage areas will not change while the robot and safety infrastructure will correspond will.

Second, two automated cells will be designed to use Fanuc robots. The first cell will be designed to use a LR Mate 200 iD/7L industrial robot. This design process will incorporate the necessary safety for the cell to be fully functional per the specifics for an industrial robot. The second cell will be designed to utilize a Fanuc CR 7iA/L collaborative robot. Consistent with the first cell, the second cell will be designed to meet the same safety and production specifications. While other robots such as the Universal Robotics UR10 are capable, the two Fanuc robots have been found to be the most comparable in size and payload while the key difference is in their ability to perform in the collaborative cell setting versus industrial cell setting. The two robots share the same design, programming and control panel.

Third, OEE will be used to study and compare the effectiveness of each cell. This process will be followed by industry standards. OEE is a long-standing metric used to evaluate effectiveness of manufacturing tools. OEE contains three parts: availability, performance and quality. Each part details the affect on OEE and with a ratio for each of the three parts, the OEE is determined.

Fourth, cost of each cell will be calculated. This will include the monetary cost of the robot and safety considerations. Additionally, other cell items including the CNC machine and CMM are set as a constant value to create a machining cell and are valuable as a point of reference for the robot integration cost. Hypothetically, if the specific cost of the collaborative robot was twice as much as the industrial robot cost, this could look significant. However, if both are insignificant relative to other costs, it will hold less importance in the overall decision of which robot to use. This is an example and will be quantified in the cost section.

Lastly, a discussion will be used to consider the results of each step summing to the effectiveness of each robot. Cost, reliability and safety are the three primary grading factors. Secondary is the efficiency of the machining process but also the space in the building. Cost is quantified in dollars while effectiveness is analyzed using OEE and quantified as a percentage. Additionally, risk assessment is factored in to consider safety concerns. The combination of all five steps will incorporate all aspects of the project and support all calculations. Weights will be given by surveying executives in the CNC manufacturing industry to validate assumptions of which factors are most significant. From the final discussion of all factors, the hypothesis can be evaluated.

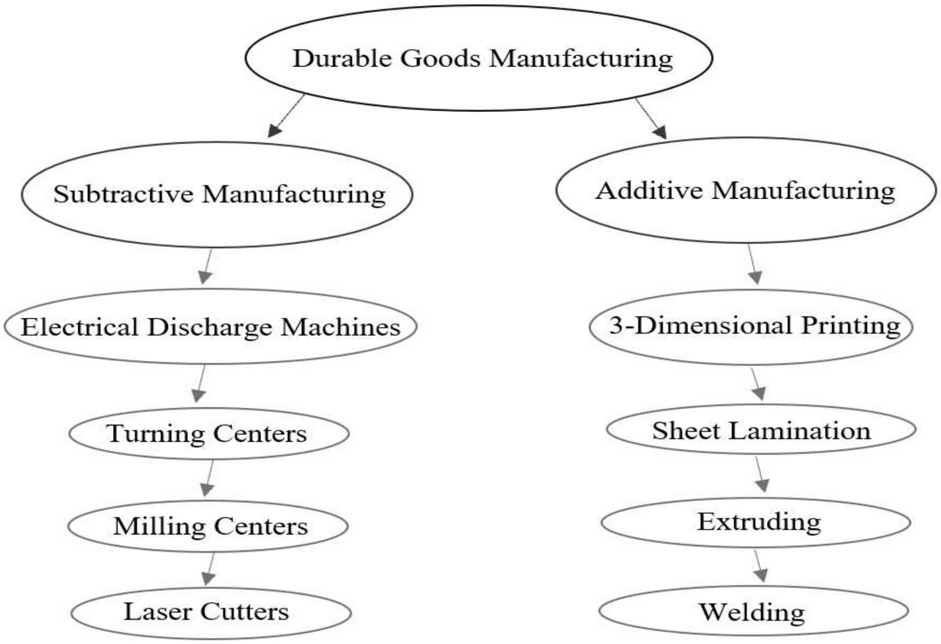
Scope

The scope of this automation is the robotic machining cell. The first item to identify is the CNC machine. In the CNC category, there are several types of machines capable of manufacturing parts and being automated with a Fanuc robot. The term CNC refers to a Computer Numerically Controlled machine and needs to be narrowed down for the scope of this project. In manufacturing, two types of goods are made; durable goods and non-durable goods. Durable goods are things such as car parts or furniture. Non-durable goods include items such as food and beverages. For the focus of this paper, machines within the durable goods category are of interest. Within durable goods manufacturing, CNC machines fall into the category of either additive or subtractive manufacturing.

Subtractive Manufacturing (SM) starts with a solid piece of stock and removes material. Commonly raw stock is extruded and saw cut to length. This process was integrated into the mass marked in the 1940s and was used to make repeatable and accurate parts. Subtractive manufacturing is most effective when making simple geometric parts containing low complexity levels. Limitations of subtractive manufacturing exist when the part has square corners or deep features. Additionally, for parts that have complex geometric features, subtractive manufacturing can be impossible or very expensive to remove material. Inherently when executing subtractive procedures, the material removed in the process is considered waste and therefore adds expense to the final product. Figure 1 depicts the concept map for durable goods.

Additive Manufacturing (AM) is the process of joining materials layer by layer to build three-dimensional (3D) objects [11]. AM was created in 1983 through the form of stereolithography. This is an effective process for manufacturing complex shapes. For this reason, the focus of this research is automating the subtractive manufacturing CNC vertical milling machine.

Figure 1: Concept Map



Scope: Data List

The items of manufacturing interest for this paper are of simple geometry and therefore will be made using the subtractive method of a vertical milling center. The table below is an abbreviated version of the full data list of the values for the robotic automated machining cell. Included in the table are the technical specifications for the items within the cell. The full table is in Appendix A: Scope. One large difference shown in the table below is the difference in weight and max linear speed of the two different types of robots. The industrial robot has an approximated max speed that is three times faster than the collaborative robot. Also noted in the Appendix, the repeatability of the industrial robot is three times higher than the repeatability of the collaborative robot. This cell data sheet will be used later in the cell design to complete a risk assessment.

Table 1: Cell Data List

Cell Data List		
Item	Value	Unit
Part Weight	<3	lbs
Part Size	3x3x3	(LxWxH) in
Space	<150	ft^2
Usage/Week	<60	hrs
Time	24/5	Hours/Day
Industrial Robot Max Speed	36	ft/s
Collaborative Robot Max Speed	6	ft/s
Effective Mass	<8	lbs
Robot Reach	36	inches
CNC Table Travel	30x16x20	(XxYxZ) inches

Cell Design: Introduction

With the scope defined, the machining cell is designed. Design has two functions related to which type of robot is ideal for automating a CNC machine. The first function of design is to make sure that the space is fully adequate for completing the task. This includes the relative distance of adjacent items. Second, validating the safety of the design in the form of a risk assessment. With the relative location of the items in the form of a floorplan, the design can be used to visualize areas of concern for an operator. Risk assessment is one of the greatest focus points of research. Risk is very important in the manufacturing environment where operators are in close proximity to danger. The risk assessment performs an analysis of the risk at all points throughout the automation process.

Cell Design: Floorplan

The focus of this research is to identify which robot is most effective to complete the machine tending task. A floorplan is developed to ensure the practical ability of the items to function as a system. Using 2-D Solidworks, each item is drawn to scale and represented in the 2-dimensional floorplan. When integrating the items into the system, the range and orientation are the greatest considerations.

For each in the two individual cells, the range of the base joint, J1, is 360 degrees. This is critical to consider because once the robot spins in a circle, it will reach its limit. An alternative way to think of it is that the robot can rotate plus or minus 180 degrees from its centerline. This is shown in Figure 2 below. This rotational limit creates a dead zone in the workspace of the robot.

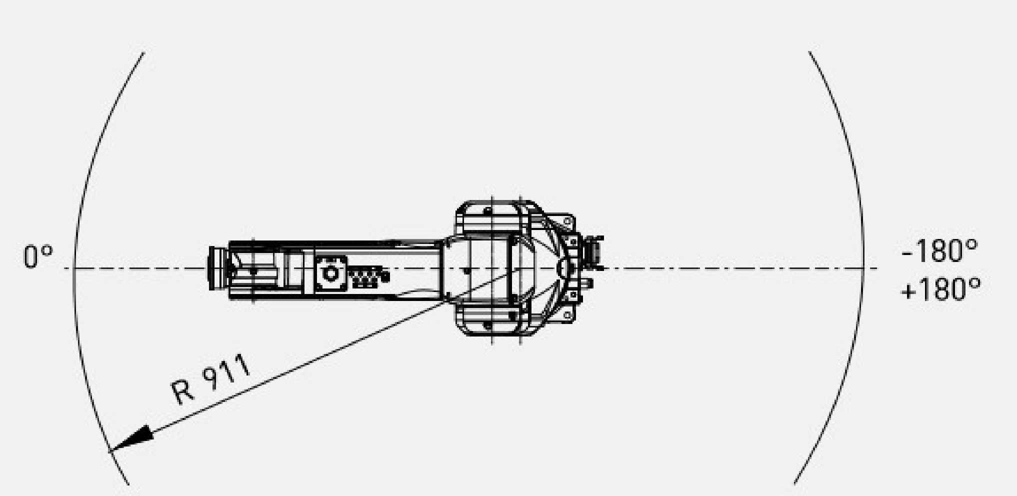
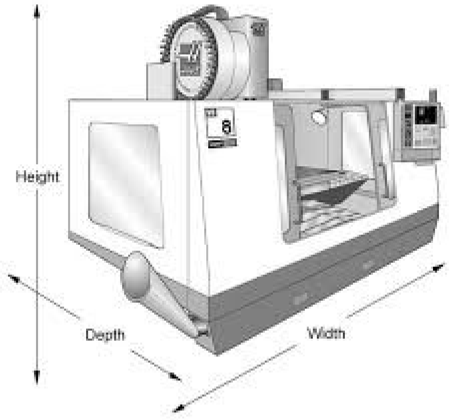


Figure 2: Robot Rotation [Fanuc 2019]

The range of a CNC machine is fully contained within the enclosure. The orientation is the main consideration when inserting into the floorplan. The CNC machine can be thought of as a microwave, it has a door on the front and the part must be placed inside through this port. Therefore, the CNC machine will have its rear direction at the back edge of the cell as a microwave typically has its back to the kitchen wall. Some machines do have side access and other unique orientations but the Haas VF2 has a front centered door. Figure 3: Haas Orientation below gives a visual of the Haas machine and dimensional directions.

Figure 3: Haas Orientation [Haas]



Safety fencing is the main difference between the collaborative and industrial cell design. This causes the floorplan to become more linear and a larger space to be consumed. In a production facility the square footage is fixed and has a high value so is potentially seen as a negative. Below in Figure 4: Safety Fencing a visual representation of safety fencing is displayed.

Figure 4: Safety Fencing [online]

The floorplans for each cell are shown in the figures below. Additionally, Table 2 shows the comparison and square footage values of each cell. The collaborative cell had an initial square footage value of 103sqft but was iterated due to some of the surrounding space not being available for other use. The new footprint size with a more box like, rectangular shape has a total of 116sqft as shown in the table below. The difference in area that each cell consumes is drastic. This is due to the safety fencing required around the industrial robot necessary to receive an adequate risk assessment value. The collaborative cell has a footprint taking up 39% of the industrial cell footprint. This is a significant difference in a small manufacturing facility.

Table 2: Space Usage Comparison

Space Usage Comparison	
Robot Type	Sqft
Industrial	296.33
Collaborative	116.17

Figure 5: Collaborative Cell Floorplan

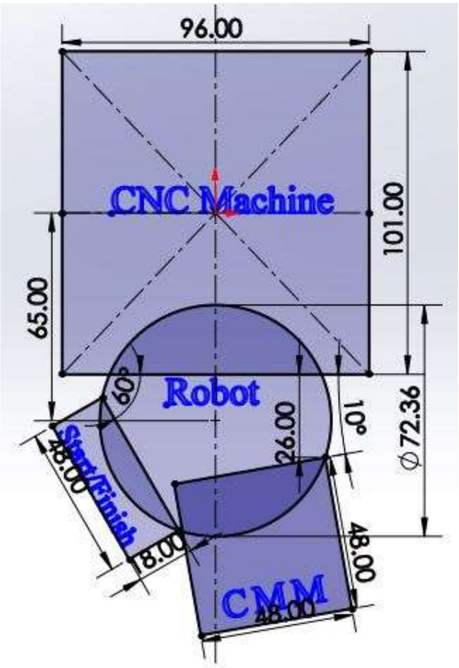
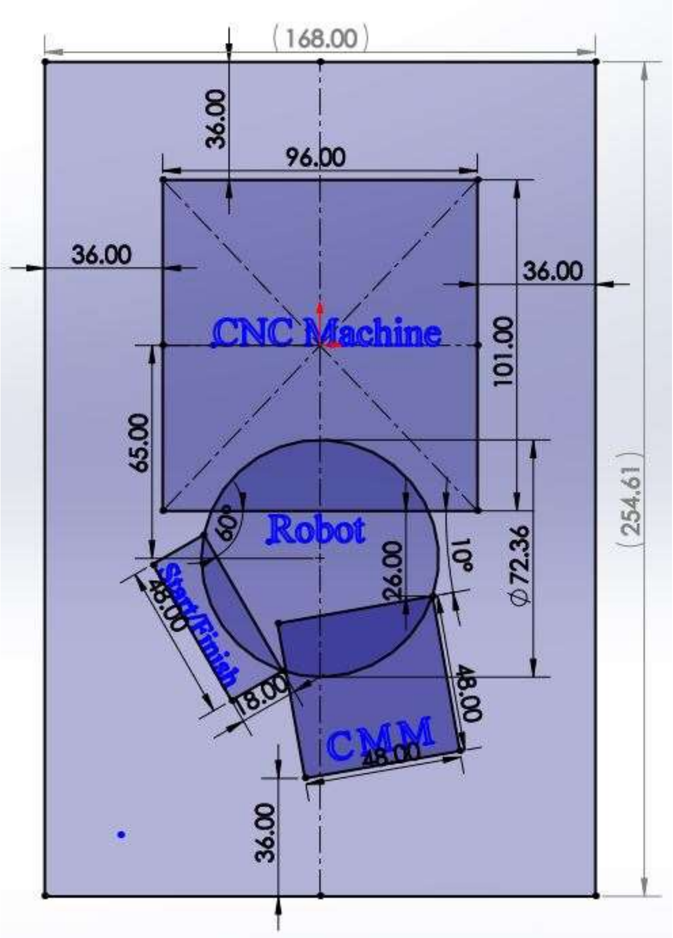


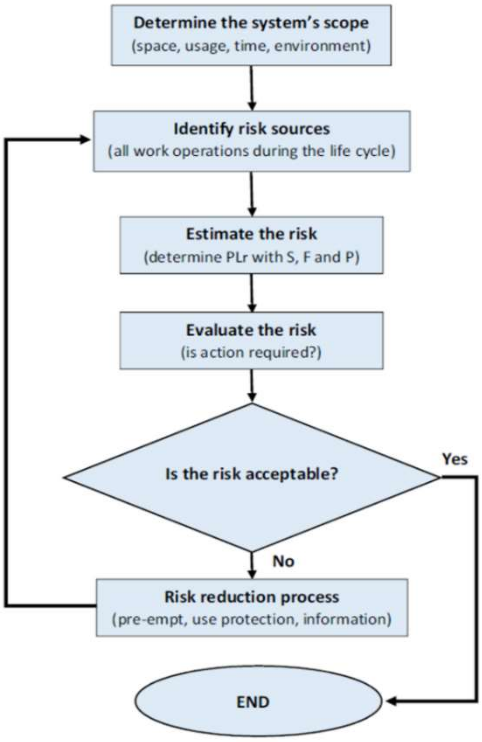
Figure 6: Industrial Cell Floorplan



Cell Design: Risk Assessment

The definition of a risk assessment is the identification, evaluation and estimation of the levels of risk involved in a situation, comparison against benchmarks or standards and the determination of an acceptable level of risk. To conform to International Standard of Organization (ISO) standards, all individual items pass through the risk assessment process from the manufacturer. However, when combing these items, an additional risk assessment must be performed to ensure the safety of the entire automation system. The risk assessment is a four to five-step process depending on if the determined risk is acceptable. This process is illustrated in the Figure 7: Risk Assessment Flow Chart below. The flow chart depicts the four necessary steps in sequential order. In the event that a fifth step for reducing risk is necessary, the process to follow for execution is outlined as well. Below, you will find a risk assessment outlined and explained through text, this outline is a standard created by ISO and not new information.

Figure 7: Risk Assessment Flow Chart [1]



As shown in the figure, scope must be defined first. Questions to discover scope include "What does the project or system include?" or "Who will be interacting with it?" Referencing the previous scope section, these details of the scope have been previously defined and can be seen in full detail in Appendix A.

Next, the different potential risks the operator could face completing the tasks of supporting the autonomous machining cell must be identified. Standard operation procedures and redundant layers of safety reduce sources of severe risk which could result in irreversible injury. Below in Table 3: Risk Identification, 5 of the greatest risks for each cell have been documented for further evaluation. 1I represents the first risk in the industrial robot cell while 1C represents the first risk in the collaborative robot cell. 1I is a risk primarily caused by CNC machine operations that are not related to the robot. When a job is complete on a CNC mill, such as the Haas VF2 in this study, things such as 6-inch vices and different types of soft and hard jaws are often changed to accommodate the next job. Due to the complexities found in manufacturing, different jobs can have varying size raw material and finish part geometry. The specifics pertaining to each unique job may require special contoured jaws. This is an example of a function involved in the machine changeover. Each robot individually undergoes the same changeover as specified in 2I and 2C. If the part varies in dimension, the gripper fingers can be removed with 2 bolts on each side to supplement for a more ideal gripper finger contour.

Risk Identification		
Op #	Operation	Risk
1I	Changeover of CNC Machine	Dropping tooling, breaking tool, crashing machine, pinch points
2I	Changeover of Robot	Dropping gripper, pinch points, robot crashing
3I	Changeover of CMM	Dropping fixture, pinch points, machine crash
4I	Resupply of Raw Material	Pinch points, misload
5I	Removing finished parts	Pinch points
1C	Changeover of CNC Machine	Dropping tooling, breaking tool, crashing machine, pinch points
2C	Changeover of Robot Gripper	Dropping gripper, pinch points, robot crashing
3C	Changeover of CMM	Dropping fixture, pinch points, machine crash
4C	Resupply of Raw Material	Pinch points, misload
5C	Removing finished parts	Pinch points

Table 3: Risk Identification

The third step in the risk assessment process is the risk evaluation. From Step 2, a total of 10 operations where risk is present have been identified and expressed in Table 3: Risk Identification. Risk evaluation looks at each operation and determines several values leading to a Performance Level Rating (PLr). The PLr value comes from three different parameters: severity of injury (S), frequency of exposure to a hazard (F) and the possibility of avoiding the hazard (P). Severity (S) of the injury is assigned one of two values: S1 a slight injury, normally reversible and

S2 a serious injury, normally nonreversible resulting in death. Frequency (F) is referring to how long a person is exposed to the hazard and how often. F is also assigned with a numerical value of 1 or 2. F1 is for an operation with seldom frequency and/or short exposure time while F2 is a frequent operation and/or a long exposure time. Lastly, Possibility (P) is determined by the likelihood of avoiding the hazard. P1 indicates it is possible under specific conditions while a value of P2 denotes it is more likely and scarcely possible.

The S, F and P values for the 10 operations are shown in Table 4: Risk Evaluation below. The S values in all 10 operations were determined to be level 1 while in the F column the values are all level 2. The reasoning for the level 2 for different operations are often different. Frequency has an and/or in the classification. Therefore, changeover such as 1I may only take place on occasion but when it does, an operator could spend a large amount of time working on the machine if a new part is being made. While risk 5I is the opposite, this risk is more frequent where the operator may be removing parts from the cell once a shift; the duration of this risk is very low. As far as the risk assessment is concerned, it is irrelevant which reason causes a level 2 frequency value.

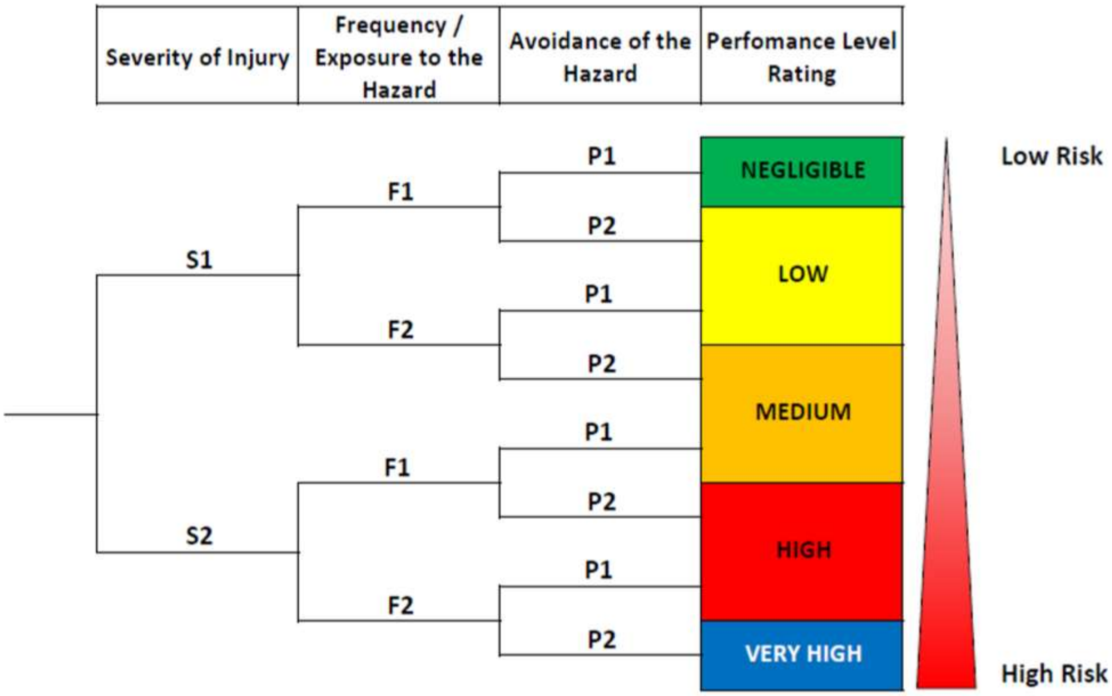
Table 4: Risk Evaluation

Risk Evaluation				
Op #	Operation	S (Severity)	F (Frequency)	P (Possibility)
1I	Changeover of CNC Machine	S1	F2	P1
2I	Changeover of Robot Gripper	S1	F2	P1
3I	Changeover of CMM	S1	F2	P1
4I	Resupply of Raw Material	S1	F2	P1
5I	Removing finished parts	S1	F2	P1
1C	Changeover of CNC Machine	S1	F2	P1
2C	Changeover of Robot Gripper	S1	F2	P1

3C	Changeover of CMM	S1	F2	P1
4C	Resupply of Raw Material	S1	F2	P1
5C	Removing finished parts	S1	F2	P1

Using the values from Table 4, the risk evaluation flow chart in Figure 8 is followed to complete the risk evaluation process. Looking at the flowchart, having an operation with potential for a severe risk leads to a high risk regardless of the frequency or possibility. Therefore, the industrial robot cell uses safety fencing making it impossible for an operator to be within working proximity of a full speed robot. However, when conducting a changeover operation, the robot can be put into a safer teach mode which limits the speed and the sensitivity at which the robot will stop moving. This results in the reduction of injury severity. For the collaborative robot in this study, the speed and sensitivity are constant which means the Cobot doesn’t cause risk of a severe injury at any time. Therefore, the Cobot does not require safety fencing to get an adequate risk evaluation value.

Figure 8: Risk Evaluation Flow Chart [1]



The result of the risk evaluation is Table 5 shown below. This is the deliverable from all steps in the risk assessment process. Using the scope to identify the operations necessary to keep the cell running, the risks were identified in Table 3. Next, the risk evaluation table was created to organize and determine the S, F and P levels for each operation. With this data, the risk evaluation flow chart is followed to determine the risk level for each operation, summing to the risk of the automated system. The last step in the risk assessment process is to set a threshold for what level of risk will be acceptable and compare this to the risk evaluation levels. Table 5 shows all the risk values are at a low level. Low risk levels produce a safe satisfactory level and therefore, no iteration needs to be done to reduce the risk of an operation. Using items such as safety fencing for industrial robots and speed and force limiting for collaborative robots allow the operation to stay in the low risk evaluation level.

Table 5: Risk Values

Risk Assessment		
OP #	Operation	PLr
1I	Changeover of CNC Machine	LOW
2I	Changeover of Robot Gripper	LOW
3I	Changeover of CMM	LOW
4I	Resupply of Raw Material	LOW
5I	Removing finished parts	LOW
1C	Changeover of CNC Machine	LOW
2C	Changeover of Robot Gripper	LOW
3C	Changeover of CMM	LOW
4C	Resupply of Raw Material	LOW
5C	Removing finished parts	LOW

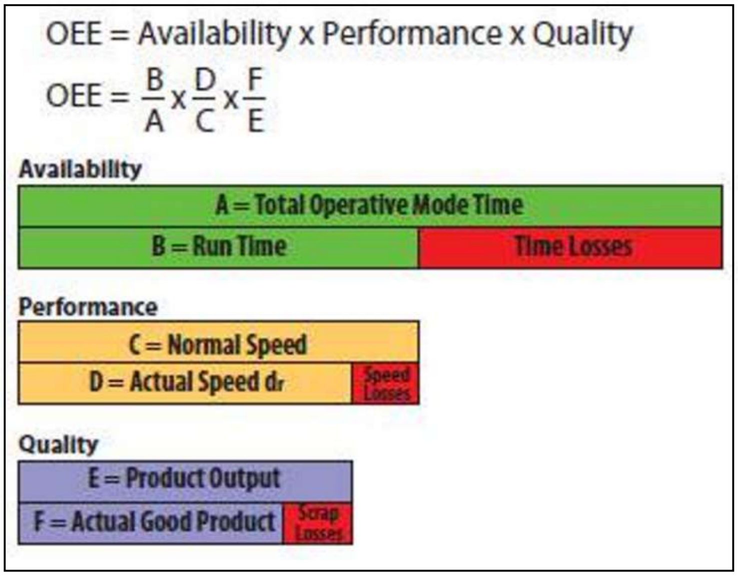
Overall Equipment Effectiveness

In production machining, the goal is to produce dimensionally accurate parts for the lowest cost possible. Overall Equipment Effectiveness, referred to as OEE, is an industry standard used to analyze different factors which influence the overarching goal of production machining. When discussing robotic automation within CNC machining, safety, improved performance, and cost are the three main concerns. With the risk assessment detailed, the effect of different types of robotic arms on OEE will be calculated. The goal of OEE analysis on collaborative and industrial robots in this setting will be to highlight the common and unique areas where they add value to the production machining.

OEE looks at effectiveness of the entire system. A clear distinction must be made between efficiency and effectiveness to understand the full value of the OEE standard. Effectiveness is calculated by looking at the potential of what could be produced compared to what was actually produced. For example, consider 10 parts can be machined per hour, but only 85 parts are produced at the end of a 10-hour shift. In this circumstance, the process was 85% effective. Effectiveness does not consider the resources involved; it only looks at theoretical versus actual output of a fixed process. Conversely, the efficiency of this 10-hour shift is a different metric. Efficiency looks at resources compared to output of a system. If the metric of a resource in is labor hours, the example of a 10-hour shift with two operators would produce 120 parts. This is a 20% increase in effectiveness of the machine; however, this is a significant loss in efficiency of the labor resource.

OEE provides a method to consider the different impacts on the bottom line of what is produced in system. OEE is composed of three categories: availability (A), performance (P) and quality (Q). Each of the three categories have the same weight in the overall effectiveness calculation. Availability refers to the amount of time the machine is available to run the desired job. Things such as changeover affect the availability of a system. Performance, second factor in the OEE equation, looks at things such as takt time to determine if the machine is running at a high level. Lastly, quality is the relationship between parts produced and parts produced containing satisfactory dimensions and surface finish values. The equation for OEE is shown in Figure 9 below. For each calculated value such as B/A, both variables have the same unit, such as time. Therefore, OEE is a dimensionless value often expressed as a percentage.

Figure 9: Overall Equipment Effectiveness [12]



Overall Equipment Effectiveness: Availability

Availability is a metric to compare the amount of time the machine can run to the total amount of time in the day. The term “capable of running” means the cell has everything it needs to make parts. The job is set up, material is ready to go in, and an entity can tend to the machine. There are several factors which cause time loss. These factors include, but are not limited to, changeover, a lack of material, broken tools and a lack of work. Additionally, when a machine can run, things such as bathroom breaks or a robot running out of raw material to load into the machine will cause the machine to sit idle. Idle time, or time when a machine can run but is waiting on an external entity to intervene, is detrimental to availability in OEE.

Table 6 shows the time loss in a week for the two robotic cells. These values are different for several reasons related to safety. The industrial robot is designed to work in an isolated area where humans are not going to interfere. For this reason, the industrial robot cell is fully enclosed with safety fencing. To resupply material or retrieve finished parts, the cell must be opened. When the cell door is opened, the robot will pause until the door is closed and the operator is clear of the workspace. When resupplying material or retrieving finished parts in the collaborative cell, the robot will operate under a double redundant safety system with speed and force limitations.

As discussed in the risk assessment, the collaborative robot can work around humans and does not need a hard safety fencing. For these operator tasks, the robot does not experience a time loss as the industrial robot does. The difference of this loss is quantified in the Time losses table below. Lastly, time loss due to changeover and maintenance of the cell is a constant between both types of robots. Some daily and weekly maintenance tasks require being in the working space and path of the robot with the enclosed CNC machine. An example of these maintenance tasks is verification by sight the machine is operating properly, such as the clearing of chips out of the CNC machine or checking the coolant mixture. The total time loss for each robot is different as seen in Table 6. The collaborative robot has 57% less time loss on a weekly basis compared to the industrial robot. This value can be misleading when not compared with the amount of time in the week.

Table 6: Availability: Time Loss

Time Losses per Week (minutes)					
Robot Type	Resupplying	Finished Parts	Changeover	Cell Maintenance	Total
Collaborative	0	0	360	210	570
Industrial	210	210	360	210	990

The calculation for OEE availability involves the time loss throughout the week versus the total time available. A robot can run unattended 24 hours a day, 7 days a week. This gives us a total operative mode time of 10,080 minutes. From Table 6 above and the ratio equation in Figure 9, the total time loss values are used to find the OEE values for availability. The results are shown in Table 7 below. Note the difference of approximately 4% availability between the two types of robots over the period of a week. This 4% compared to the 57% less time loss the collaborative possesses compared to the industrial robot.

Table 7: OEE: Availability

Overall Equipment Effectiveness: Availability			
Robot Type	Hours Available	Time Lost	Availability Ratio
Collaborative	10080	570	94.35%
Industrial	10080	990	90.18%

Overall Equipment Effectiveness: Performance

Performance of the machining cell is determined by how fast the cell could run compared to actual takt time on a weekly or daily basis. This is affected by all items in the cell. For this examination, however, the performance of the robot is most important. In an automated machining cell, the CNC machine is not being adjusted regularly by an operator, therefore assumed it runs at 100% as well as the CMM machine. Performance of a robot involves repeatability and speed. The repeatability of both the industrial robot and cobot are very small and insignificant as a difference to focus on. It is standard on a tolerance block for a part drawing the tolerance of a dimension is plus or minus .005 thousand of an inch. With the cobot having the less repeatable data out of the two robots, it is still less than 10% of the tolerance available for a good part to be made. For this reason, the focus of robot performance will be on speed.

The robots in this experiment are defined by their scope, they each have the same 6 joints and build construction. In terms of the robot arms travel velocity, the collaborative robot has a speed limited as deemed safe around humans. This difference between the max speed will determine the OEE performance ratio. Shown below in Table 8 are the speeds of each joint of the industrial robot. The speed for each joint of the collaborative are limited to 250 degrees/second. The build construction and capacity of the robot are the same. When a robot is programmed to move, each joint varies in speed to keep the gripper in the proper vector orientation. Since each robot has the same construction, they will be following the same relative tool path. The way a Fanuc robot is programmed with FINE and CNT points and parameters defining speed limits will affect the TCP path. This experiment assumes they are following the same program and neglects other programming differences for simplicity. The relative speed of the cobot to the industrial robot is the focus of the data analysis of speed to performance. It is assumed the limiting joint to the speed of the industrial robot will be the same for the cobot. This means the industrial robot determines the normal speed for OEE of performance and the cobot is always operating at a speed loss.

Table 8: OEE: Performance

Robot Speed Data			
Robot Type and Joint	Industrial (deg/s)	Cobot (deg/s)	Cobot/Industrial
Robot Max Speed J1	370	250	67.57%
Robot Max Speed J2	310	250	80.65%
Robot Max Speed J3	410	250	60.98%
Robot Max Speed J4	550	250	45.45%
Robot Max Speed J5	545	250	45.87%
Robot Max Speed J6	1000	250	25.00%
Average Speed	530.83	250	54.25%

The OEE performance value for the industrial robot is 100%. In the future this could be challenged from another robot programmed in a similar environment with different programming structure or different gripper systems. These things do not play a significant role in this research because the changes would be constant between the two robots. The challenge of performance would have to come from a industrial robot. The cobot OEE value for Performance is 54.25%. This value is significantly less than the industrial performance level. Both of these values will factor into the overall equipment effectiveness.

Overall Equipment Effectiveness: Quality

Quality determines whether the parts manufactured satisfy the drawing. When a part is machined, the machine must be programming so the cutter knows where to go and what material to remove. The drawing specifies everything about the part including geometric dimensions and tolerances, material, coating and surface finish. The part is then inspected once machining is complete to ensure the machining operation removed the proper amount of material. In the robotic cell, a coordinate measuring machine (CMM) is used to geometrically inspect the part. Traditionally in production facility, CMM machines and the time it takes to tend the machine is very expensive and therefore it is very costly to measure every part. With the set-up of this machining cell, this traditional limit is avoided. This is related to the robot being about to tend to the CMM and the CNC machine. Additionally, having each part inspected as they are being machined, if there is a fault that occurs with the machining process, the CMM will catch it and the cell can stop in order to reduce the amount of defective parts. This shows that each of the different factors in OEE can affect each other but balance out. In traditional effectiveness studies, if the machine kept running it would show high effectiveness but with OEE it would be worse to keep running making faulty parts because OEE encompasses and quantifies all parts of the process to make a good part.

The OEE factor of quality in this study will be equally represented with a value of 1 between the two robotic cells. Although robots significantly increase the quality of manufacturing through reliability and consistency compared to humans, the intention of this research is to compare robots. Using humans as a point of reference can be helpful to give a situation connection to the current method used in industry. The comparison to humans for the quality factor is very complex and will not be used for reference. For this case, the quality value of 1 could be removed to simplify the equation. It will remain as reference in the case this process is being replicated to compare robots under different circumstances.

Overall Equipment Effectiveness: Results

Using the equation from Figure 9, the OEE for each cell is calculated. Each factor value for the three categories of availability, performance and quality are shown in Table 9 below. The assumptions made during the calculation of each of these values were vast. The OEE of a robot depends greatly on the area where it will be functioning and the proximity of people. As shown below, the difference in OEE based on availability due to the robot stopping when an operator resupplies the cell was insignificant in this case. This could vary in different machining environments. In the OEE calculation the biggest factor is performance. Having a robot perform at a reduced speed is satisfactory in a circumstance where it is necessary to keep a specific level of safety. In the case of machining tending, having a robot perform at a reduced speed to maintain a collaborative state was detrimental to the OEE of the cobot cell.

Table 9: Overall Equipment Effectiveness: Results

Overall Equipment Effectiveness				
Robot Type	Availability Factor	Performance Factor	Quality Factor	OEE
Industrial	0.9435	1	1	94.35%
Collaborative	0.9018	0.5425	1	48.92%

Cost

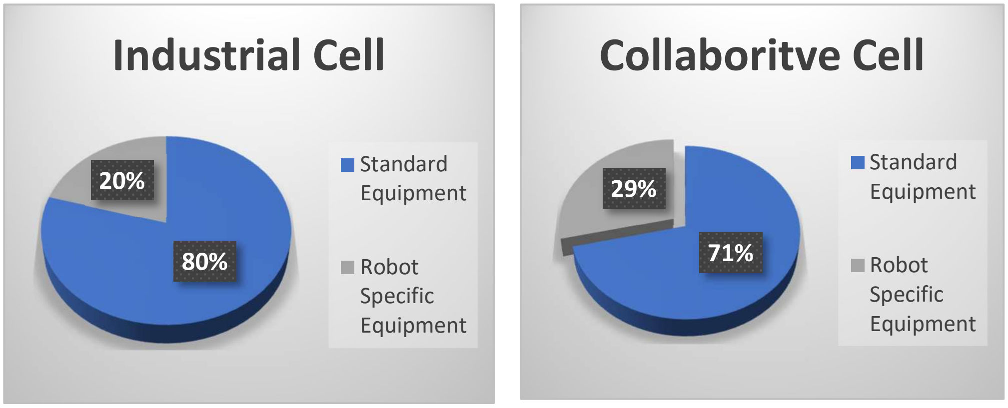
What is sacrificed in order to acquire a product or service is the cost. Cost of robotic automation develops in three forms: monetary, square footage and resource form. Each of these forms has an impact in determining the opportunity for profit from an investment into a new system.

First, the monetary cost is quantified in the unit of dollars and is composed of equipment. The equipment included in this cost is the robot, CNC machine and other peripheral items specified in Table 10: Equipment Cost, shown below. In the table, the constant cost of creating a machining cell is expressed. Following these equipment costs, the specific cost to add each type of robot is detailed. The difference in cost between a Fanuc CR 7id Collaborative robot and the industrial Fanuc LRmate 7id is $22,000 and is a 40% difference. The significance of this value depends on the context of the system automation. If the cell is being designed and build from an empty space, as this discussion considers, this value is less significant compared to an existing CNC machining cell a robot is being used to automate. Looking at the Robot cost relative to the Standard equipment needed to machine is shown Figure 10: Relative Cost. These figures were created using the values from Table 10. From the figures, the collaborative equipment cost composes approximately 9% more of the total equipment cost compared to the industrial cell.

Table 10: Equipment Cost

Equipment Cost		
Items:	Qty	Cost
Haas VF2 SS	1	$ 79,575.00
Hexigon CMM	1	$ 45,000.00
Robotic accessories	1	$ 8,000.00
CNC Machine acc.	1	$ 5,000.00
	Subtotal	$ 137,575.00
Industrial Cell		
Fanuc LRmate 7id	1	$ 32,000.00
Safety Fencing	1	$ 3,440.80
	Subtotal	$ 35,440.80
Collaborative Cell		
Fanuc CR 7id	1	$ 54,000.00
Light Curtain	1	$ 1,500.00
	Subtotal	$ 55,500.00
Industrial Cell Total		$ 173,015.80
Collaborative Cell Total		$ 193,075.00

Figure 10: Relative Cost



Second, the cost of square footage in a manufacturing facility. Depending on the facility, space may be more valuable than others. The difference in square feet for each cell comes from the safety fencing required to have an industrial robot. This value is difficult to quantify in terms of cost. The data shows the industrial robot cell is 61% larger than the collaborative cell for this machine tending scenario. This will have to be weighed by the facility looking to automate the VF2 machine to determine the impact.

Lastly, the cost to integrate each of these in terms of resources within the company will be the same relative cost. Although things such as safety fencing require more to cost to install, the cost is shown monetarily. This section of company resources is referring to the additional energy spent for modified fixturing or different machining programs that send out values to the robot for crash prevention for example. Like the OEE quality factor of one, because each cell has relatively the same cost this will not factor into the cost to integrate.

Results and Discussion

The results of the experimental cell analysis are shown in Table 11, below. This table compiles the results from all the previous sections outlined in the methodology. There are significant differences between robotic cells in the footprint and overall equipment effectiveness. The cost difference to create each robotic cell is less substantial a difference. It was previously discussed in the cost section, if a cell with a machine is already in existence and the addition of a robot is the focus, cost difference will have more significance.

Table 11: Results

Results	
Cell Design: Footprint	
Industrial Cell	296.33 (sqft)
Collaborative Cell	116.17 (sqft)
Risk Assessment	
Industrial Cell	LOW
Collaborative Cell	LOW
Overall Equipment Effectiveness	
Industrial Cell	94.35%
Collaborative Cell	48.92%
Cost	
Industrial Cell Total	$ 173,015.80
Collaborative Cell Total	$ 193,071.00

Safety fencing has a significant impact on the footprint of an individual machining cell. The collaborative cell is 39% of the industrial square footage. This can be reduced in several ways. For example, if two machines are confined by one safety fencing, the perimeter distance between each machine would be reduced. Following this change, the entire methodology would need to be repeated to determine the affect on risk and OEE. It is likely the difference in footprint is also insignificant compared to the substantial increases in throughput from a faster robot.

The risk assessment proved to be a surprise. The marketing and spoken of value for collaborative robots has greatly been safety related. This research shows for tending a has VF2, the risk factor of using a collaborative vs industrial robot is negligible. This is a significant discovery in leading industry 4.0 in the direction of the most effective machine tending solution. With the risk values determined to be constant between the two types of robots, the focus shifts to overall equipment effectiveness.

The overall equipment efficiency value differences are the second large discovery of this experiment. The performance difference between each robot has a significant impact on the effectiveness. This is the two robots relative to each other. The impact of takt time of each machining cycle and other factors such as CMM time will also play a role. This analysis gives a point of reference for studying robotic automation of production machining.

It is clear with consideration of each factor or this thesis experiment, the industrial robot is more conducive to the VF2 for production machining. The almost doubled level of performance while still maintaining an equally safe if not safer risk assessment. The impact of the specific workpiece also has an affect on the risk assessment. Using safety fencing to enclose the entire cell makes it so that the workpiece difference between jobs does not require the same level of intensity to determine safety. Attention would still need to be focused on the robot when automating a new job to make sure the part fits within the payload capacity of the robotic arm. Additionally, the robot gripper also needs to apply a gripping force strong enough to overcome gravity and the forces created when the robot is moving around at a high speed.

Future Work

The research of robotic automation of CNC machines is essential to creating the most effective production environment. There are many different facets of automating a vertical milling machine that were not covered in this research. Several case studies following the methodology of this experiment will be very valuable to validate the data discovered in this research. The greatest future work should be in keeping a constant level of risk assessment when machining different parts. This is an additional area where have safety fencing seems to be the robust and most effective long-term solution to keep the operator and the robot safe. When the geometry and material of the machined part change, the collaborative classification is no longer valid. The risk assessment must be executed again to ensure operator safety. Is safety fencing the solution to this time-consuming process?

Appendix A: Scope

Cell Data List		
Item	Value	Unit
Part Weight	<3	lbs
Part Size	3x3x3	(LxWxH) in
Space	<150	ft^2
Usage/Week	<60	hrs
Time	24/5	Hours/Day
Effective Mass	<8	lbs
Robot Reach	36	inches
Max wrist Capacity	15	lbs
Industrial Robot		
Industrial Robot Max Speed J1	370	Degree/s
Industrial Robot Max Speed J2	310	Degree/s
Industrial Robot Max Speed J3	410	Degree/s
Industrial Robot Max Speed J4	550	Degree/s
Industrial Robot Max Speed J5	545	Degree/s
Industrial Robot Max Speed J6	1000	Degree/s
Industrial Robot Max Linear Speed	36	ft/s
Repeatability	0.0011	inches
Mechanical Weight	60	lbs
Collaborative Robot		
Max Speed J1	250	Degree/s
Max Speed J2	250	Degree/s
Max Speed J3	250	Degree/s
Max Speed J4	250	Degree/s
Max Speed J5	250	Degree/s
Max Speed J6	250	Degree/s
Max Linear Speed	6	ft/s
Repeatability	0.000393	inches
Mechanical Weight	121	lbs
Haas VF2-SS		
CNC Table Travel	30x16x20	(XxYxZ) inches
Spindle Speed	12000	Rpm
Max Cutting Speed	833	ipm
Max Rapid Speed	1400	ipm
Chip-to-chip	3.6	seconds

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