

Automated Laser Marking Machine

A Baccalaureate thesis submitted to the
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College of Engineering and Applied Science
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requirements for the degree of

Bachelor of Science

in Mechanical Engineering Technology

by

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ABSTRACT

Looking back on some of the most rewarding and challenging moments of this project, I feel that the experience obtained throughout this process has been very beneficial for me moving forward. Having the opportunity to work with my employer to create a demonstration resource that the company will be able to utilize for years to come has provided me with invaluable industry experience and technical know-how. The project began during the Spring Semester of 2017 while on my fourth co-op rotation, and the opportunity arose after an acquisition was made by my employer of another automation distributor/integrator in the region. After moving facilities and obtaining an extensive new list of vendors, I was given the opportunity to utilize both a Universal Robots UR3 collaborative robot and a Datalogic AREX optical fiber laser for my capstone project here at UC. Over the course of the next few months, I focused on generating ideas for the project and homing in on my proposed concepts to determine which ideas were most realistic and fulfilled each of the requirements set by my employer. The key, as I will outline in more detail throughout this report, was to utilize the various components that I was provided to showcase the integration of these devices as they work alongside one another to complete a series of tasks.

After being involved in many conversations with coworkers and supervisors, I was given the go-ahead to select a final concept, at which point I began ordering the materials required for construction. This process was inclusive of selecting the pen that I would be using for the marking process, ordering various electro-mechanical components required for operation, and finally gathering the raw materials used for construction of the robotic cell. Once materials began arriving, I started to prioritize tasks in a more logical sense, based exclusively on their significance and in what order the processes needed to be completed. Fabrication and assembly of the laser marking robotic cell was followed by construction of the UR3 base and custom assembly of the Rittal electrical enclosure which houses the core system processing and communication devices. From here, I tested the basic functionality of each electrical component, established communications between each device respective to the PLC, and began implementing the program logic.

The programming aspect of this project, particularly in dealing with Siemens' TIA Portal software, was quite extensive and required many revisions before reaching the final product.

Although the logic was very sequenced and organized, there were many techniques that I was otherwise unfamiliar with prior to taking on this work. Function blocks were used for each of the three major program elements (robot, laser, and turntable operation), which were all stored in one organizational block. A series of data blocks were used for storing tag parameters, and MOVE blocks designated the beginning and end of each task, with integer tags being manipulated to transition effectively from one task to another. Strings of hexadecimal characters were required for communication to-and-from the Datalogic fiber laser. Each string's respective header, content, and end sequence were unique from one another based on the message length and type of command. Upon starting the program, the PLC would recite the opening of the laser template, changing one of the text fields to include the user's name, and beginning the marking process once the pen was determined to be in position underneath the laser marking head.

In all, I am very pleased with the final product and certainly feel that the many months of hard work required to reach this point paid off. Like most others, I encountered challenges and shortcomings along the way, but I learned some very valuable lessons in doing so which I wouldn't been provided had I not been given the opportunity from my employer to take on this task. Upon graduating from UC in the coming weeks, I'm confident that I'll have many chances to apply what I've learned from this capstone project in the real world.

PROBLEM DEFINITION AND RESEARCH

PROBLEM STATEMENT

The motivation behind this particular machine is to incorporate all of the major product lines that my employer has to offer into one complete package. This device will be used primarily in trade shows to showcase the integration of various product lines following the recent acquisition made by my co-op employer, Electro-Matic Products, of RAF Automation.

BACKGROUND

The history of this problem has been rapidly evolving from a conceptual standpoint over the last two decades. With the insurgence of industrial automation products into the marketplace (particularly Programmable Logic Controllers), ideas which seemed far-fetched and rather daunting years ago have developed into commonplace features in factories, laboratories, and even amongst everyday items found on the streets and in commercial environments. Fully automated laser marking processes occur every day in a multitude of ways, but utilizing a multi-axis, collaborative robot along with a motorized turntable are few and far between.

Throughout my research, I've discovered that a handful of devices operate using a PLC and a variety of electrically- or pneumatically-driven sliding or rotating mechanisms to reposition objects for the laser marking process. (1) For this application, a major point of emphasis during the brainstorming process was to make this system adaptable and entirely modular for other potential projects down the road, which is very difficult to find elsewhere in the market. Having the ability to remove the electrical control box, collaborative robot, or laser from the assembly to use independently of one another when otherwise required by the user adds a distinct advantage to this design. Companies like Keyence, Laserax and Autolase offer similar products, but fully automated turn-key solutions are custom produced on an order-by-order basis with no modularity. With internal, adjustable optics, the AREX Laser Marker will allow for fine tuning adjustment before and during the marking process. (2) In addition to this, the unit's marking head is among the smallest and most capable in the industry. (2)

RESEARCH

SCOPE OF THE PROBLEM

Understanding that this product is being used as a demonstration resource during trade shows and company sponsored events, the design must encompass these traits versus that of a high-speed production line item. The reasoning behind addressing this problem is because the project's primary contributor, Electro-Matic Products, requested that the original Datalogic Laser Marking demo be repurposed to showcase and incorporate additional moving parts, along with our other flagship product lines (e.g. Siemens, Turck, Rittal, etc.). This project is important because it greatly influences our customers' perception of our brand and quality. It also acts as a uniquely interactive device which pulls the user into the interface and introduces them to Siemens' programming architecture, among many other elements being implemented.

CURRENT STATE OF THE ART

The technologies that have been researched throughout this process include a variety of stand-alone, industrial-grade laser marking devices along with other multifunctional, logic-driven enclosures which utilize sensors, electric motors, user interface devices and safety components. When looking in-depth at the competition, it's clear that many similarities exist in the marketplace, yet all of these examples are specifically designed to be used in intense factory automation environments versus being used solely for demonstration purposes.

The most comparable and competitive products on the market today include the Wisely Automated Laser Marking Table, the ElectroX Pen Marking System, and the Lasit Fiber Fly Programmable Laser Machine. (1) First and foremost, the Wisely machine's core mechanism utilizes a key component that I'll be using in my project – the electric turntable. Its speed, consistency, and ease of use make this device a formidable competitor, and certainly one that I'll be observing closely during the design and build process. However, this machine is only capable of marking pens or other small, uniformly shaped objects. (2)

Next, the ElectroX conveyor system uses translational movement to transfer the blank pens into the marking enclosure, with the finished products exiting on the opposite end soon thereafter. Pros of this product include reliability, safety, pleasing aesthetics, and easy to

maintain. (1) Similar to the Wisely machine, the ElectroX lacks in versatility, is expensive, difficult to set-up, and must be transported using a large vehicle. The Lasit Fiber Fly shares nearly identical characteristics as the ElectroX considering they utilize virtually identical hardware and software elements, with the exception of slightly improved aesthetics, improved quality, higher cost, and reduced mobility. (1)

With that being said, keeping the cost down is very important, but so is striking an even balance with an equal part of newly released, industry-leading hardware and software products that will remain relevant for years to come. As it has been noted before, modularity is vital for this product design. As opposed to the competition, having each major component removable makes it possible to dedicate these expensive pieces of equipment towards other tasks and makes set-up, teardown and transportation much easier. (3) Also, having sturdy, fixed brackets makes set-up very repeatable while keeping the consistency of operation very high. With this demo designed to be taken out by salesmen and other non-technical employees, it's important to keep the simplicity of these tasks in mind.

Lastly, extensive research has lead me to believe that one characteristic lacking from the competition is quick, easily adjustable side-to-side and vertical members used to resituate the laser for other items to be engraved. When investigating turn-key laser marking systems, collaborative robots, and multi-axis gantry systems, the resounding element lacking in these solutions seemed to be modularity, mobility, and cost. (3) By breaking apart each major component, Electro-Matic will be able to either utilize the combined pieces to perform the designated task, or nominate each subassembly to be used for other demonstration or training purposes.

Part of creating an effective trade show device is having the understanding that customers want to see something unique each year. Running the same demonstration, using the same giveaway items tends to become rather dry and forgetful after an extended period of time. Having the ability to manipulate the design each year to incorporate state-of-the-art elements whenever desired adds an entirely new dynamic to the device in the long run.

END USER

The customer's needs demand that the device be intuitive, interactive, and produce consistent results. More specifically, the process from start to finish should be fluid while

remaining safe from any outside infractions. The logic must also successfully convert the user input onto the pen accurately. The customer for that this product will pertain to the most is exactly what the subheading implies – end users. Contrary to original equipment manufacturers or machine builders, end users will see similar products on a day-to-day basis as they work on with conveyor systems, processing lines, laser engraving/printing procedures, and other high-speed applications.

Requirements for prospective customers include robustness, speed, maneuverability, worker safety, efficiency, sorting ability, load capacity and initial cost. By showcasing proven, battle-tested brands like Siemens, Universal Robots and Turck, Electro-Matic is able to remain very competitive in these categories. From my experience and research, I've come to find that our product lines generally fall within or below the expected range of our customers cost expectations. (5) Quality is also a major point of emphasis for these companies, so keeping the enclosures, brackets and other custom built pieces as aesthetically pleasing and professional as possible is also important in the eyes of both customers and other industry representatives.

CONCLUSIONS AND SUMMARY OF RESEARCH

To conclude this portion of the report, it should be noted that a number of themes have been reoccurring and should be emphasized by how they specifically tie to the potential customer. Many end users who use similar products want to see distinct advantages over the competition which might include, but are not limited to speed, accuracy, fluidity, ease of use, and aesthetic appeal. In an effort to maximize interest while reducing the risk of errors, the device will be equipped with various field sensors along with a detailed logic program to minimize undesired faults.

CUSTOMER REQUIREMENTS

As for conducting surveys regarding this product, I chose to gather information from several colleagues and other individuals familiar with the industry/marketplace. This includes a Factory Automation Specialist, Industrial Control Specialist, Project Manager, various Application Engineers and a few prospective 'buyers'. By surveying and gauging their level of interest in the product and what key features stood out to them, I was able to generate a

more well-rounded concept moving forward.

My interview with George Levanoff, an experienced Automation Specialist dealing exclusively with PLC's, drives, and HMI's gave me a great perspective of what Electro-Matic might like to see as well as what customers will find most appealing. By formulating a weighted importance level for each engineering requirement, I found that the machine's overall weight, emergency stop response time, and total duration of marking process turned out to be the four most crucial factors to consider as I moved toward the design process. These comparisons and results can be found in the House of Quality below, as a part of the Quality Function Deployment process.

PRODUCT OBJECTIVES

Customer features were addressed by demonstrating effective use of the materials provided while offering a customized item for the user to take home. Material selection and machining techniques were consistent throughout, while vendor products remained clearly visible to demonstrate their respective capabilities as intended. With electrical equipment displayed through a viewing window on the Rittal enclosure, customers have a clear visual of the key Siemens components inside. Ultimately, the customer wants to see a fluid sequence of events, superior build quality, and an aesthetically pleasing design.

QUALITY FUNCTION DEPLOYMENT

Title: Automated Laser Marking Machine
 Author: Michael Hawthorne
 Date: 9/14/2017
 Note:

Legend

- ⊕ Strong Relationship 9
- Moderate Relationship 3
- △ Weak Relationship 1
- ++ Strong Positive Correlation
- ⊕ Positive Correlation
- ⊖ Negative Correlation
- ▼ Strong Negative Correlation
- ▲ Objective is To Minimize
- ▲ Objective is To Maximize
- X Objective is To Hit Target

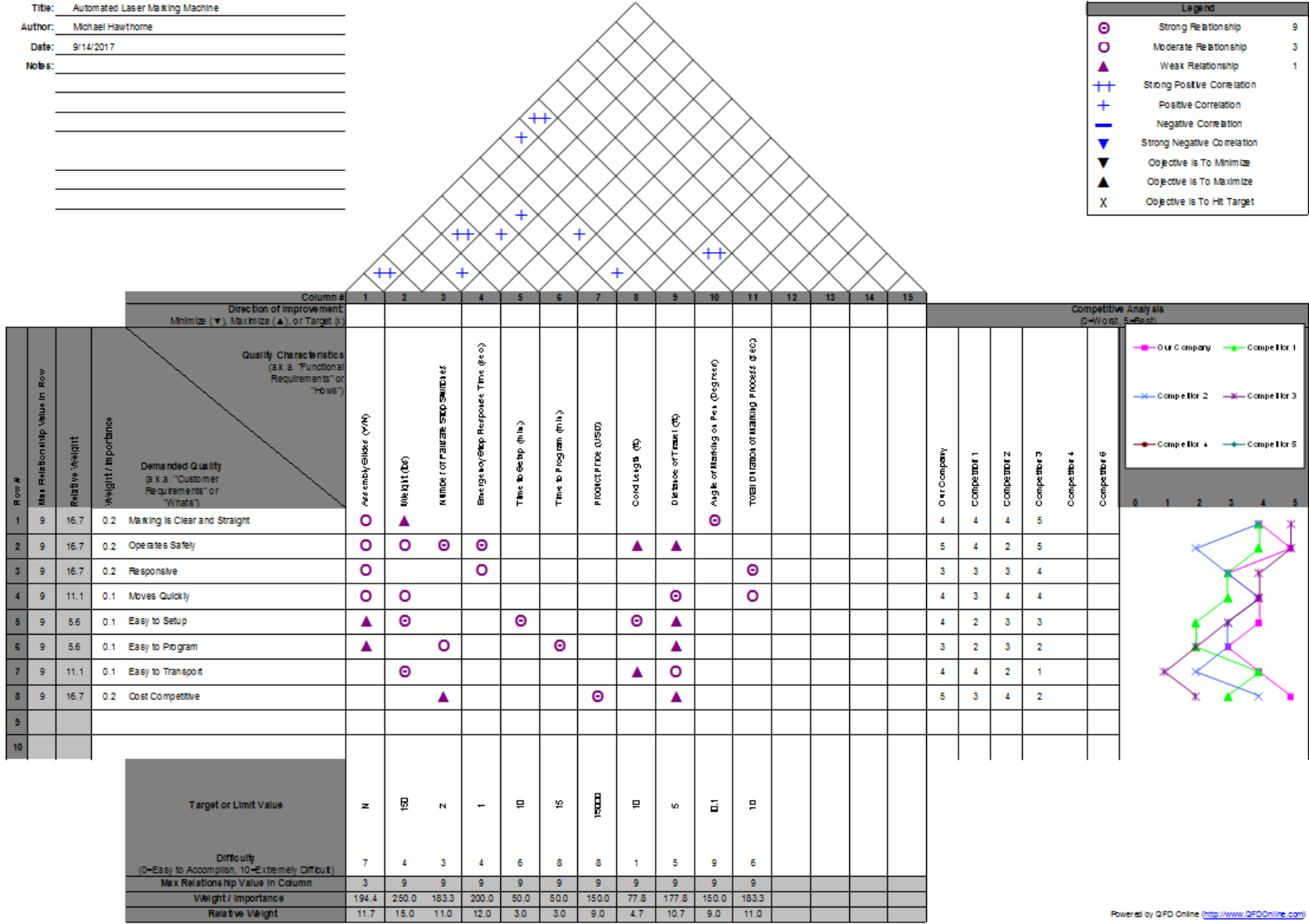


Table 1: Quality Function Deployment

The final list of key design features includes a rigid frame with simple fastening brackets, use of a collaborative robot with standalone control box, free-standing electrical enclosure, and an easily adjustable turntable.

DESIGN

Design alternatives and selection

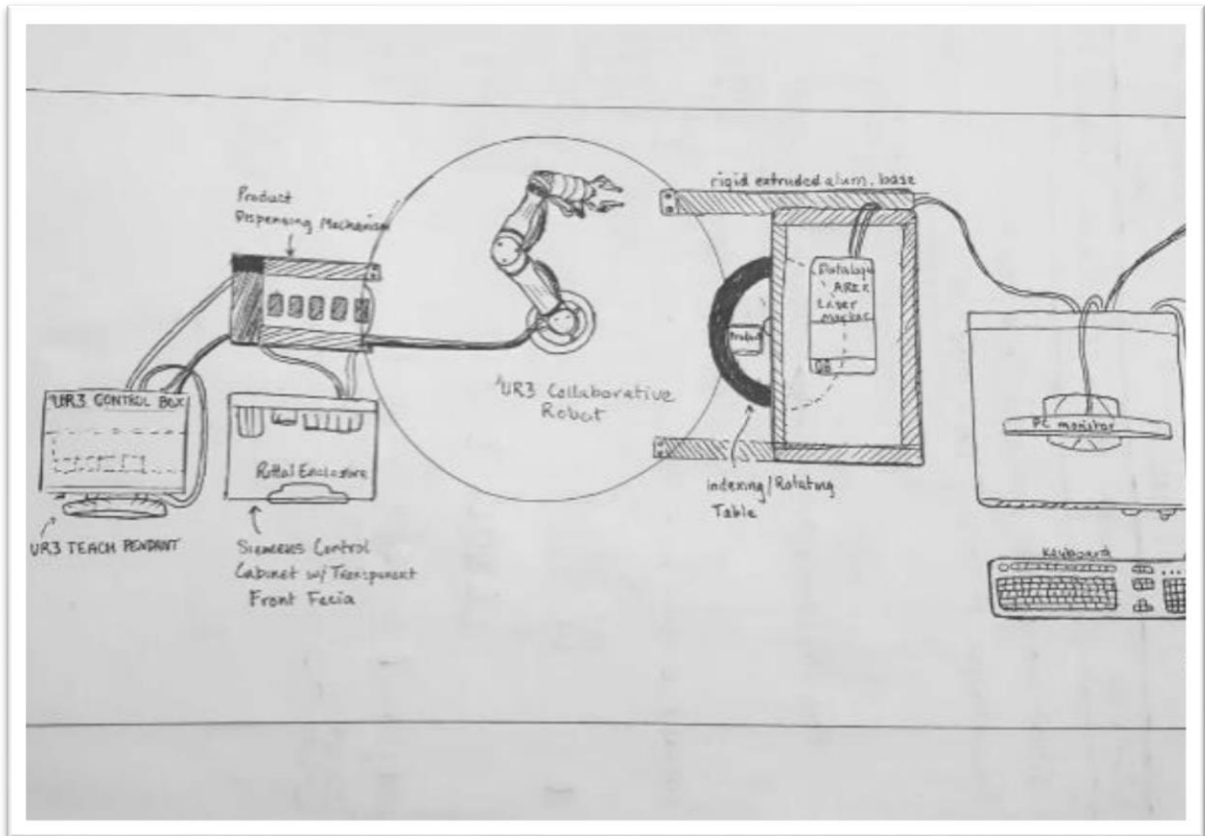
Design alternatives were ultimately narrowed down to three possible configurations,

each with their own unique and defining characteristics. While considering these options, the major contributing factors that were considered for a final selection included cost effectiveness, availability of materials, accuracy/precision, aesthetic appeal, overall complexity, and ease of use/setup. To begin, the first concept features an all-electric design with a low-voltage, reversible DC gearmotor powering a turntable fastened to the laser enclosure's wall. Concept #1 also utilizes minimal external sensing devices and provides a layout that is easy to manage.

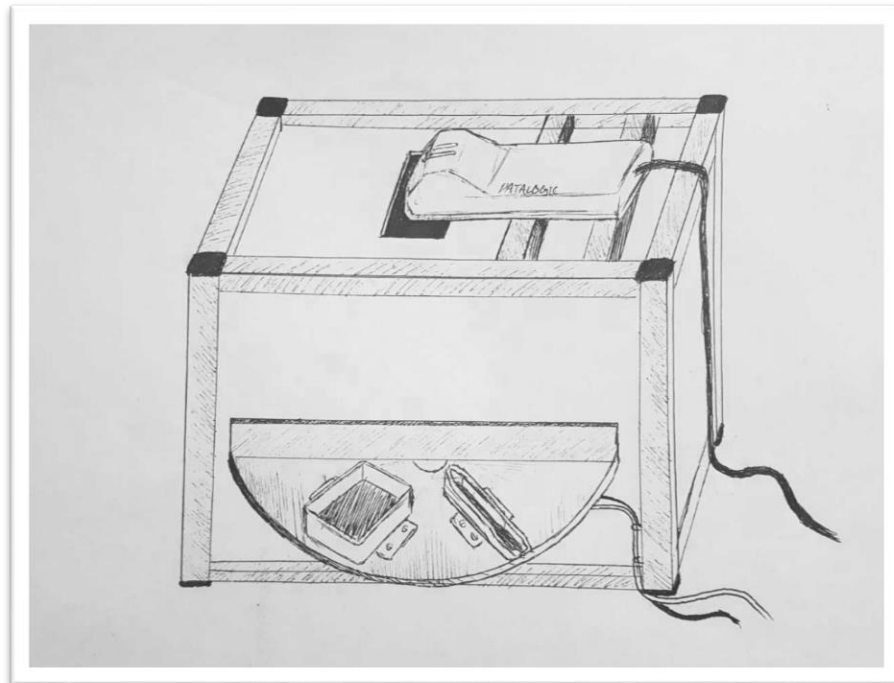
The second concept design substitutes a pneumatic linear actuator for the electric turntable, thus featuring a Festo valve bank, tubing, and a conventional ball screw linear actuating device. Despite having more-than-capable precision, thrust, and duty cycle requirements, this setup requires air prep and additional components for the pneumatic operation which burdens both ease of use and overall cost effectiveness. The third and final concept eliminates the need for a mechanical, moving device on the laser marking enclosure and instead relies entirely on the positioning capabilities of the UR3 collaborative robot. By essentially removing all electro-pneumatic cords/tubes to the laser marking enclosure, adding transparent glass around the enclosure, reducing weight of the assembly, and minimizing the number of moving mechanisms, this configuration is simple and draws the users attention towards the versatility of the UR3. The major drawback for this configuration is that repeatability can be difficult to achieve over time without a vision system or other external sensing devices.

Ultimately, I chose Concept #1 based on its combination of readily available and cost effective materials, entirely electrical system design, and more consistently precise positioning without the need for additional external sensing devices.

Drawings



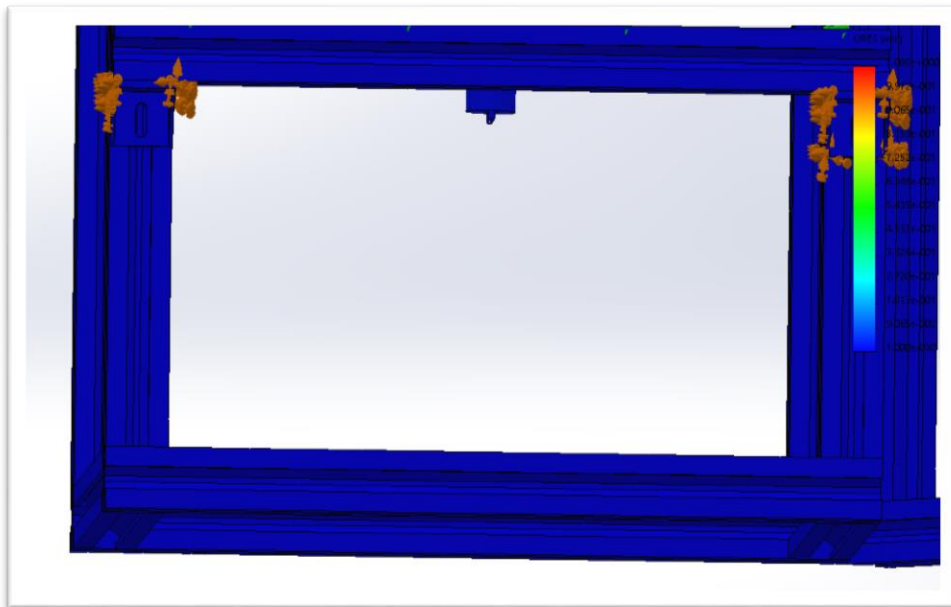
| Figure 1: Original Topology Sketch



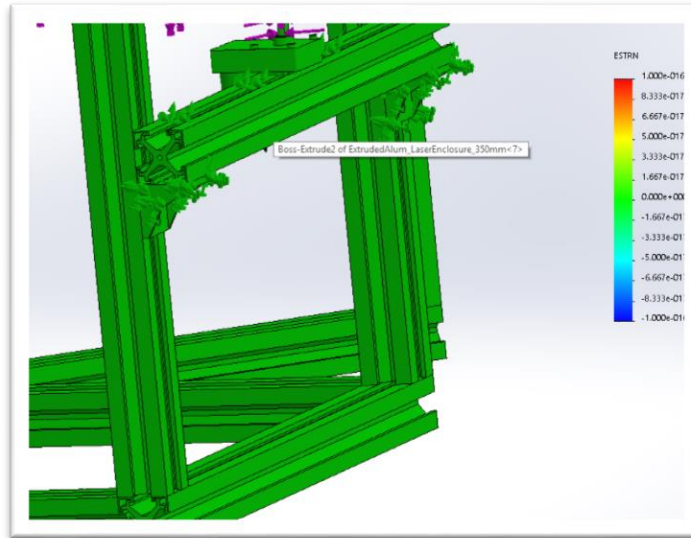
| Figure 2: Laser Marking Enclosure Sketch

Loading Conditions

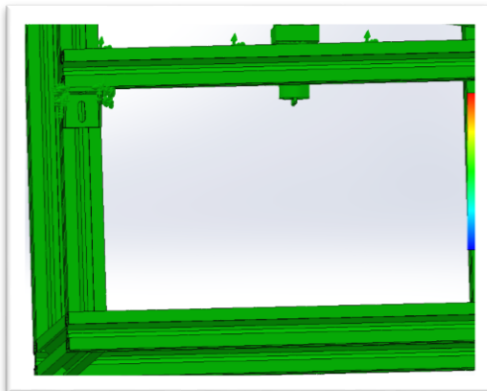
With the exception of the excessively capable UR3 payload (3kg lifting a ~0.005kg pen), the images below depict the comprehensive stress-strain analysis on the horizontal support member with linkages on opposing ends for the turntable. This includes the maximum rotational force being applied by the motor and full load bearing with the hardware depicted. As illustrated, the stress, strain, and deformation on the horizontal support member are very minimal, if not negligible. The RobotUnits 40x40mm structural aluminum being sourced for this application is designed to withstand very large payloads and sufficiently greater forces than what is being applied here.



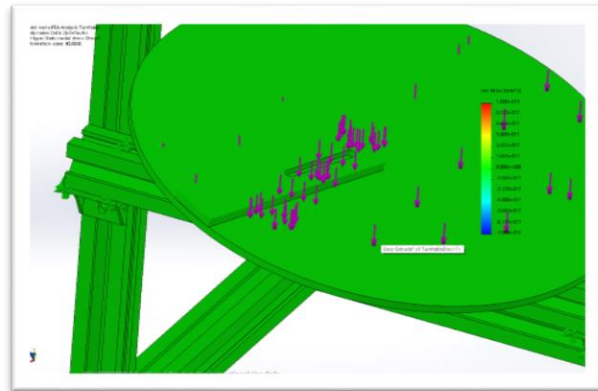
| *Figure 3: Displacement on Horizontal Support Member*



| *Figure 4: Stress/Strain on Turntable and Supports*



| *Figure 5: Stress/Strain on Enclosure*



| *Figure 6: Stress/Strain on Turntable*

Design Analysis

Throughout the Design Analysis process, a number of variables were thoroughly considered before proceeding with final fabrication and assembly processes. To begin, all measurements were carefully drawn out and modeled in Solidworks prior to execution. This includes creating a template for the cuts required on the faceplate of the Rittal electrical enclosure (HMI, Pushbuttons, etc.), generating a rough sketch of the enclosure backplane which was followed up with precise markings for the drilling/tapping processes, implementing previously used base configuration designs for the UR3 and adjusting them slightly to mate directly with the laser enclosure, and simply generating an outline for all other extruded aluminum frames and custom brackets. Understanding the relative dimensions of each component being placed within the electrical enclosure was important when

determining the size and quantity of din rail being used as well as choosing the appropriate quantity of wire to be used.

I went with a relatively conventional layout with the electrical enclosure, aside from adding the optional clear acrylic viewing window cutout. Heavy duty, steel 40mm-square RobotUnits brackets were used for mounting of the laser head module, horizontal turntable support member, and connectors to link both the laser marking enclosure and the robot's base together. During the ladder stages of construction, the decision was made by my supervisor and myself to include an electrical component stand to hold the control units for each device. The design also used Maytek extruded aluminum, similar to what was being utilized for most other structural support pieces on the laser enclosure and UR3 base. Casters were added to the stand's feet for added mobility while an adjustable 2-bar linkage monitor mount was installed for visual feedback of the Datalogic laser during operation. Images of this setup can be referenced in Appendix A.

Factors of Safety of Concern

Given the fact that virtually every element of this complete assembly has been overengineered (as outlined above in the Loading Conditions summary), the primary concern of mine when considering the Factors of Safety of Concern involved the potential risks for pinching points, exposure to harmful laser light/radiation, and any risks of electrical shock. Given the fact that I'll be utilizing a rigorously tested and certified collaborative robot, most factors of safety involving this device have already been addressed/integrated within the program logic by means of internal force-torque sensors and standard safety parameters. Additionally, I'll be using a fail-safe Siemens S7-1511F CPU with integrated safety logic, emergency stop switches, and overload protection which minimizes the risk for system failures and damage to the equipment.

Component Selection

Component selection was quite straight-forward for this project, given the fact that I was originally supplied with the Universal Robots UR3 and Datalogic AREX laser marker. From here, I proceeded to design the system with extruded aluminum, sized an appropriate Rittal enclosure given the criteria noted above with the help of our Rittal specialist Sarah Groden,

and simply chose viable, relatively low-cost components supplied by our list of vendors in all other areas. More specifically, the 24V DC power supply was chosen based on the cumulative amperage of all other electrical components, and since I wanted to keep the design within the enclosure uniform, I choose between two variations of the “S7-1500 family” 24VDC power supply units.

The selection of the reversing contactor was based on the requirements for this application, and an electrical schematic of the unit verified my understanding of its operation. The aluminum used for the custom motor bracket, disk-to-shaft adaptor, and pen holsters were all sourced from scrap pieces left over from other in-house injection molding machine builds. Finally, the motor voltage regulator was sourced from a 3rd party vendor and sized based on the specifications of the selected 24V DC, 1.1A gearmotor. The 24V-to-12V stepdown device for the Rittal enclosure LED lighting was also supplied through an online vendor.

Bill of Material

The BOM for this project followed suit with the information provided in the Component Selection summary above. A comprehensive cost analysis is included as well. This list includes:

Bill of Materials with Cost Analysis		
Description	Quantity	Cost (USD)
Universal Robots UR3 Collaborative Robot w/ Control Unit	1	26,000.00*
OnRobot 2-Finger Mechanical Parallel Gripper	1	3200.00
Siemens TP700 7" Touch Comfort Panel HMI	1	2400.00
Siemens PM1507 Power Supply, 120VAC to 24VDC, 8A	1	458.98
Siemens Reversing Contactor w/ Integrated Busbar	1	126.60
Siemens S7-1511 CPU, PLC	1	1,749.46
Siemens Analog AI/AQ Card, 16x2	1	832.00
Siemens Digital DI/DQ Card, 16x2	1	696.00
Siemens Momentary 22mm Push Button, Green, Illum.	1	22.63
Siemens Emergency Stop Pushbutton, 22mm, Twist Release	1	32.50
16 Gauge Wire Spools, Blue/Blue and White, 20 ft.	1 Ea.	42.50
Turck 8x14GA Comm. Cable with Quick Disconnect	1	33.23
Turck Bulkhead Ethernet Connectors, IP67 with Cap	2	146.00
Turck Proximity Sensor NI10U-M12E-AP6X-H1141	1	172.50
Turck Proximity Sensor Mounting Bracket	1	8.50
Turck 5M Proximity Switch Cable RK 4T-2/S101	1	42.98
Robotunits Extruded Aluminum, 40mm x 40mm	1500mm	356.00
Robotunits End Caps, 40mm x 40mm, Black	16	59.00
Maytek Extruded Aluminum, 40mm Square, T-Slotted	4500mm	721.00
Maytek Aluminum Casters, Pre-Assem. w/ Hardware	4	36.00
Maytek Anchored Perpendicular Connectors	20	245.00
0.236" ABS Sheet, 72" x 72"	2	71.60
Robotunits Steel 90° Mounting Bracket with Hardware	12	263.82
Datalogic AREX 50W Fiber Laser with Control Rack	1	22,000.00*
DAYTON 24VDC Gearmotor, 50 in-lb Reversible 1.1A	1	54.65
Aluminum 12"D x 1/4" Thick Disk, CNC Machined	1	102.76
24VDC Motor Speed Controller 0.1-10 Amps	1	24.99
12VDC LED Light Strips, 12"	1	8.99
24VDC to 12VDC Step-Down Voltage Regulator	1	12.00
Siemens Terminal Blocks, 8WA1011-ODG22 x10 QTY	2	18.00
Siemens Shielded Profinet Cable, Cat5e	50 ft.	369.89
Rittal Command Enclosure, 15"x15"x10" w/ Handles	1	948.62
Siemens 180° Ethernet Connectors	8	98.20
Excluded from total, already provided for project		TOTAL: \$13,354.47

| Table 2: Budget

PROJECT MANAGEMENT

BUDGET, PROPOSED/ACTUAL

The proposed budget for this project is \$15,000, which does not include the UR3 Collaborative Robot and Datalogic AREX Laser Marker. Upon completion, the final cost

came out to \$13,354.47. The original estimate was obtained through our inside sales specialist, Ross Delia, who confirmed all order requests and manually entered the information into our online ordering system’s Sample Demo Account. With no major failures during the machining, assembly and testing processes, the project came in roughly 11% under budget.

SCHEDULE, PROPOSED /ACTUAL

The schedule below depicts a combined proposed vs. actual timeline of events and compares their anticipated date of completion to actual figures. The highlighted column represents the final week of January for reference, and testing was completed late February prior to two major technical trade-shows in the Midwest which the demonstration was used in mid-March (both the ADM Expo and Manufacturing in America). I attended the Manufacturing in America expo event to man the booth as well as partake in setup/teardown of the assembly from March 13th through the 15th. The project was perceived very well, with over 400 pens being marked and given away in addition to over 100 opportunities/leads with customers following each event, respectively. An image from this event can be found on Page 21, Figure 18. A graphical depiction of the schedule can be seen below.

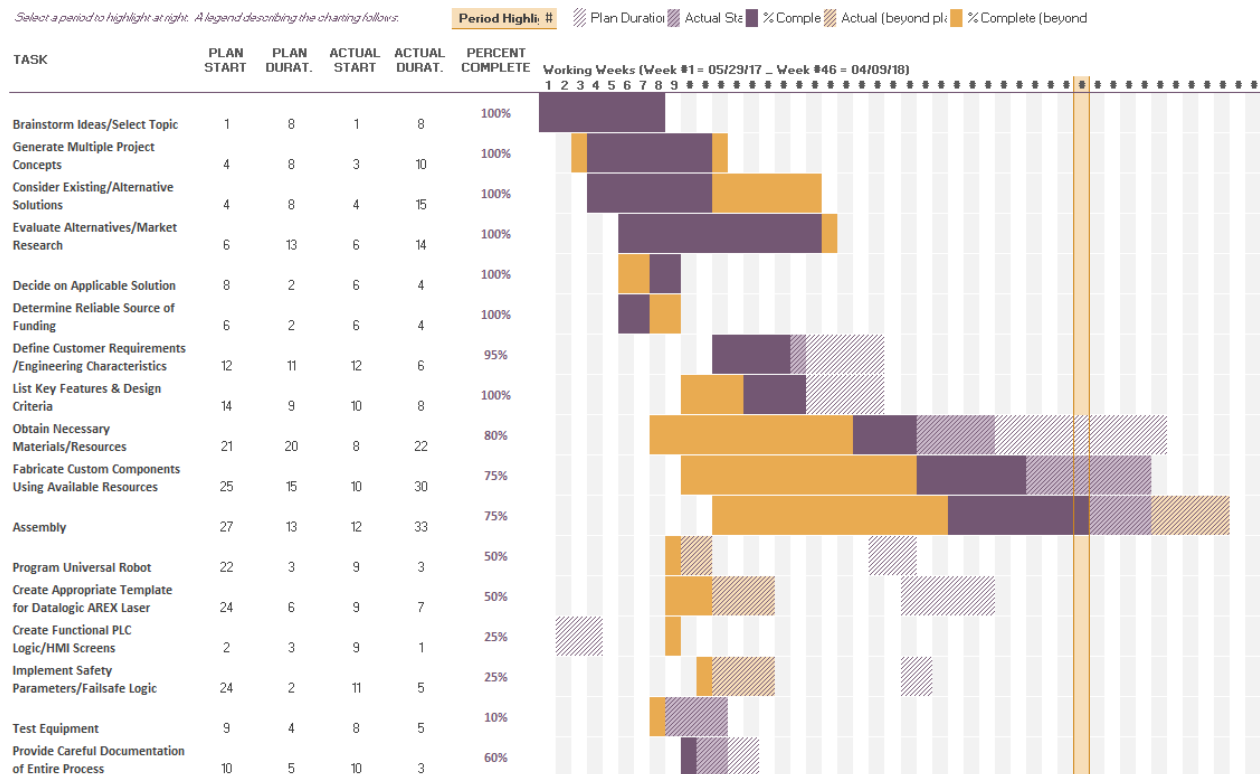


Table 3: Schedule

PROGRESS IMAGES



| *Figure 7: Working Assembly without Stand*



| *Figure 8: Laser Marking Enclosure*



| *Figure 9: Pre-Assembled Electrical Enclosure*



Figure 10: Electrical Enclosure Faceplate



Figure 11: Electrical Enclosure Assembly

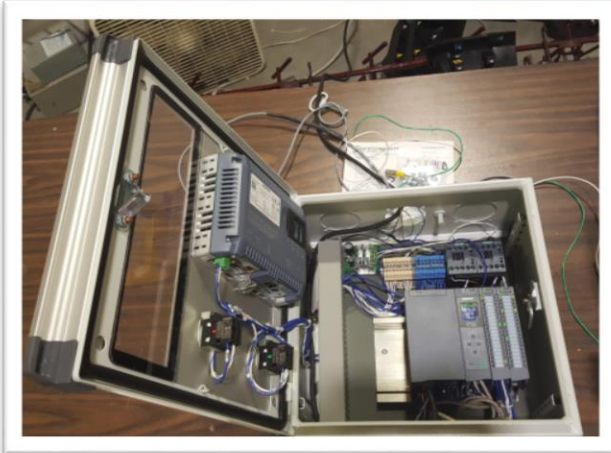


Figure 12: Electrical Enclosure Interior with Wiring

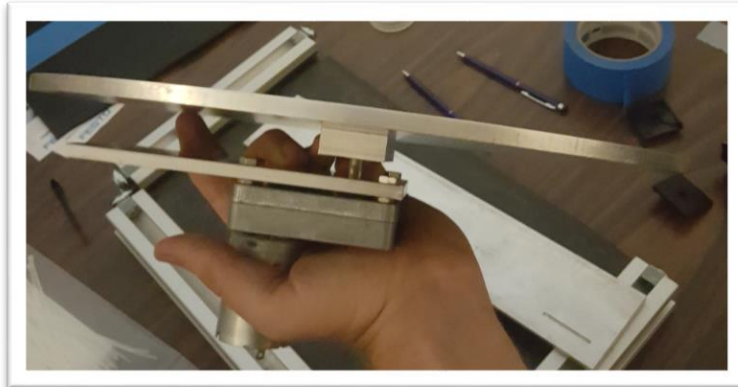


Figure 13: Turntable Assembly



| *Figure 14: Laser
Marking Enclosure Top*



| *Figure 15: Turntable Disk*

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APPENDIX A: ELECTRICAL STAND

Illustrations of the electrical components stand along with photos of the project during use.



Figure 16: Electrical Control Stand Model



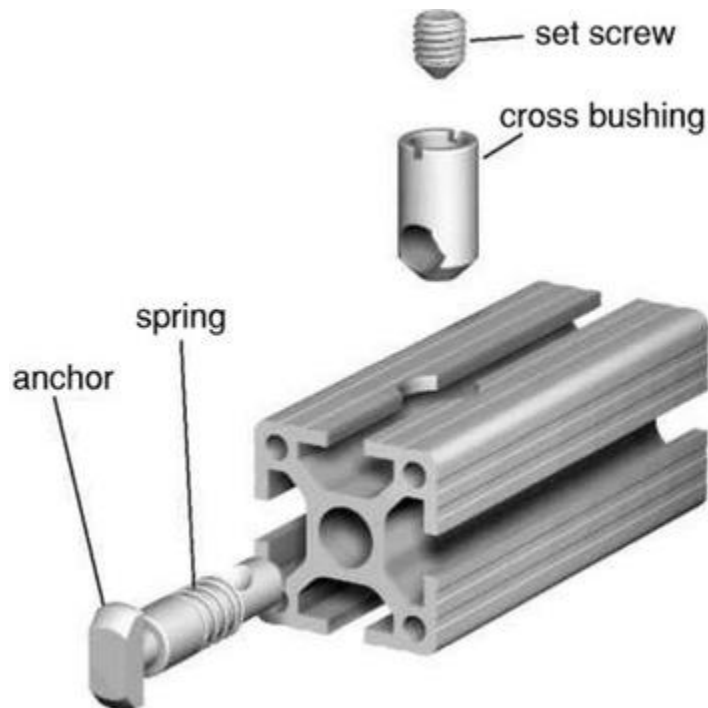
| *Figure 17: Electrical Control Stand Assembled*

Electrical Components Stand which houses the Rittal Electrical Enclosure, Universal Robots Control Unit with Teach Pendant, Datalogic AREX Controller Rack, and external monitor for laser feedback information. (February, 2018)



| *Figure 18: MiA Showcase*

Image taken from Manufacturing in America 2018, where the demo was used for 2 consecutive days successfully marking over 400 pens.



| *Figure 19: Maytek Aluminum Connectors*

Design features of the Maytek structural aluminum perpendicular connectors.

APPENDIX B: PROCESS TIME

Clock Time	Robot Position	Operation	Time Required	Scheduled Completion
0	A	Open Gripper	0.3	0.3
0.3	A	Pickup Pen at A	2.5	2.8
2.8	A	Close Gripper	0.3	3.1
3.1	A	Move to B	3.8	6.9
6.9	B	Load Machine B	2.2	9.1
9.1	B	Open Gripper	0.3	9.4
9.4	B	Machine at B	35.5	44.9
44.9	B	Unload B	2.2	47.1
47.1	B	Move to A	2.8	49.9
49.6	A	Dropoff Pen at A	2.5	52.1
52.1	A	Machine at A	0	52.1
. Cycle Time = 52.1 Seconds .				

| Table 4: Process Time

$$3600 \text{ (sec/hr)} / 52.1 \text{ (unit/sec)} = 69.23 \text{ units/hr}$$

*With a cycle time of 52s, the production rate with these parameters is **69.23 pens/hour**.*

APPENDIX C: CALCULATIONS

The following calculations were required for sizing an appropriate DC gearmotor, later used for turntable positioning.

$$\text{Circumference of Turntable} - 2 \cdot \pi \cdot r, 2 \cdot \pi \cdot 6 = 37.6991 \text{ in}$$

$$X = 37.6991 \text{ in -OR- } \mathbf{0.9575 \text{ m}};$$

$$X/2 = \mathbf{0.4788 \text{ m}} \text{ (linear travel of pen per active sequence)}$$

With a target of 1 second per half-rotation of the turntable, both the velocity and acceleration are..

$$V = 0.4788 \text{ m} / 1 \text{ sec, or } v = \mathbf{0.4788 \text{ m/sec}} \quad a = \mathbf{0.4788 \text{ m/sec}^2}$$

$$\text{Mass of Aluminum Disk} = 0.1(\pi \cdot r^2 \cdot h), = 0.1(\pi \cdot 6^2 \cdot 0.25) = \mathbf{2.827 \text{ lbs}}$$

$$\text{Mass of Pen} = \mathbf{0.0058 \text{ kg}}$$

Force Required to adequately rotate turntable. *Mass = weight of disk + mounting hardware + pen, rounded up.

$$F = m \cdot a, F = (1.908232) \cdot (5) \quad F = \mathbf{9.54116 \text{ N}}$$

$$9.5412 \cdot 0.45681 = \mathbf{0.0045681041 \text{ kW}}, \text{ so...}$$

$$\text{Torque} = \mathbf{4.5681 \text{ Nm}};$$

By analyzing this torque with a desired speed of 30 RPM, the resulting power is
0.00613 HP

Mounting position: After finding the exact center of the aluminum disk using the two-chord method, the base dimensions were best suited at 2.38" apart. This distance permitted sufficient clearance from the motors shaft while allowing me to utilize the provided rectangular 3"x2"x1" aluminum block as a motor-to-disk base/adaptor. This centerpoint was verified using a specially designed tool by my coworker and master craftsman Tim Munroe.

A McMaster-Carr Compact Square-Face Gear Motor was used to drive the system, and the specifications for this include: 24VDC, 47 RPM @ 448 in-oz, 1.1 Amps @ Full Load, 0.02 HP – Part #:6409K27

Alum. Plate = 0.25"x12" Diameter

| *Figure 20: Turntable Calculations*

APPENDIX D: PROGRAMMING

The three programming interfaces used for implementing system logic and utilized for testing/simulation include Siemens TIA Portal V14, Datalogic Laser Lighter Suite, and Universal Robots URScript. Images depicting each of these software architectures are shown below, respectively.

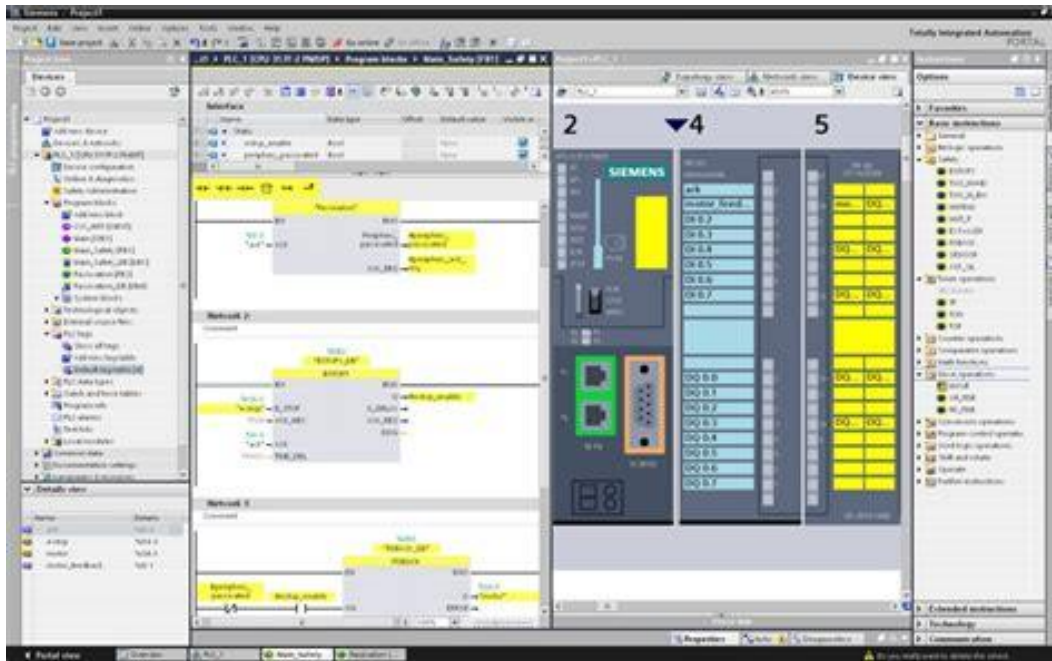


Figure 21: TIA Portal Interface

Siemens TIA Portal V14 via Siemens Field PG

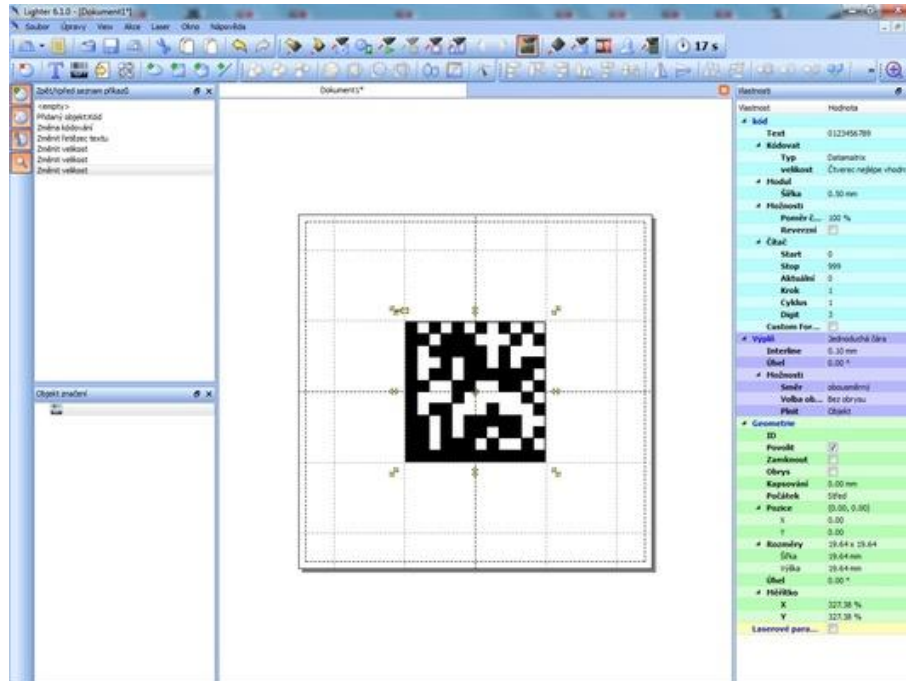


Figure 22: Lighter Suite Interface

Datalogic Laser Lighter Suite via Control Rack Interface

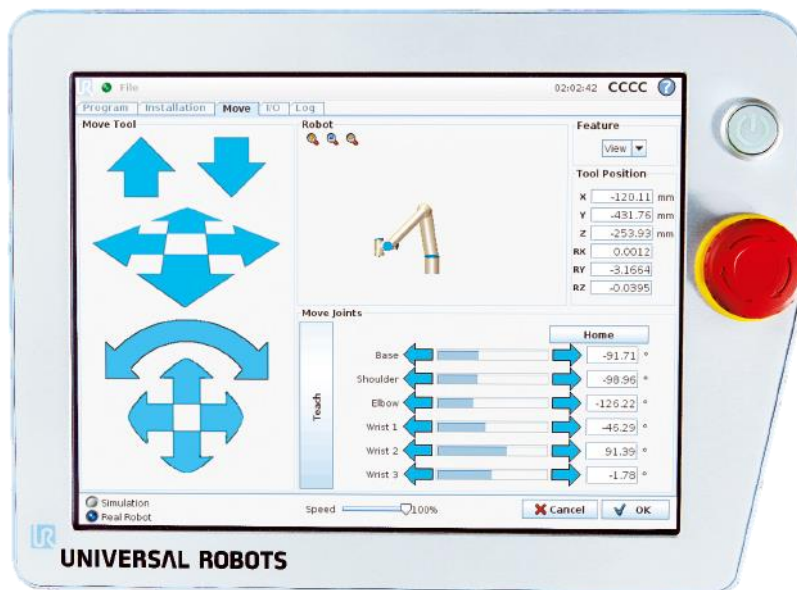


Figure 23: URScript Interface

Universal Robots URScript via Device's Integrated Teach Pendant