# MSD 2 Technical Report

P16601: Glass Fab - Multi Wire Saw Glass Cutting Machine: Guide Rollers

Members: Ryan Cavanaugh, Samantha Degerick, Evan Ney, Noah Stransky, Quincey Stuck, Viniamin Tokarchuk, Kenneth Wilkinson

---

<u>Background:</u>

The mission we were tasked with for our Multidisciplinary Senior Design (MSD) journey was to create a glass-cutting machine for low volume production. Glass Fab Inc., a local Rochester, New York company, called upon us to create this machine. Glass Fab was founded in 1974 with their main production focused on cutting precision optical glass blanks for the vast optical industry in Rochester. Glass Fab first came in contact with the R.I.T. Mechanical Engineering Department in the fall of 2014 to explore the possibility of creating a scaled-down version of their current glass cutting machine, the Meyer Burger DS 264. This machine consists of two guide rollers that rotate simultaneously and are wrapped with an array of fine brass coated wires. As these wires move horizontally, a glass ingot (or work piece) is fed into the wire array, cutting the ingot into thin wafers or blanks. The Meyer Burger DS 264 is made for high volume production with the capability of up to 4100 cuts per ingot and using one 47kW motor per guide roller. Glass Fab regularly uses the DS 264 to make 30-300 cuts per ingot, which makes for a very inefficient and energy intensive process.

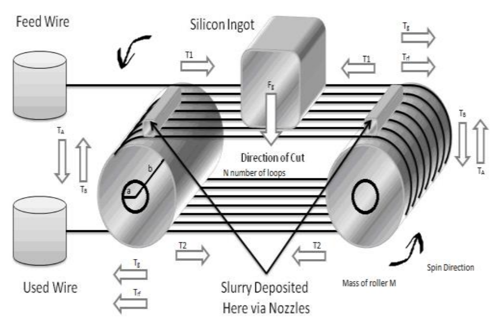


**Figure 1:** Wire saw concept sketch

After numerous visits to Glass Fab and thorough analysis of the feasibility of the project, the R.I.T. Mechanical Engineering Department took the project to the spring 2015 Design Project Leadership (DPL) class. A team of five DPL students was assigned to the project to become familiar with the current machine, comprehend the customer expectations, and develop the engineering requirements. This team created a Project Readiness Package to pass off to future Senior Design teams. In this package, the team transferred knowledge of the customer’s requests, potential design concepts, preliminary engineering requirements, constraints, deliverables and required skills.

In the Fall of 2015, 21 students were assembled to carry out the project. The project was split into three subsystem teams: P16601 focused on the guide roller assembly, P16602 focused on the wire movement, and P16603 focused on the workpiece movement. Each team consisted of four Mechanical Engineers, two Electrical Engineers and one Industrial and Systems Engineer. Our team specifically was the P16601 Guide Roller team. The first half of the fall semester focused on defining engineering and customer requirements, benchmarking and extensive research on our specific subsystem. The second half of the fall semester was spent on detailed design work, definition of components and metric comparison to the DS 264. The spring 2016 semester then focused on further definition of the design, design alterations, system integration and the purchasing requirements and process. The details of our 30 week Guide Roller journey will be further expanded below.

<u>Benchmarking, Research, and Engineering Requirements:</u>

Our senior design journey began with a deep dive into benchmarking and research. The biggest influence in terms of benchmarking and research into glass cutting was Glass Fab's existing machine, the Meyer Burger DS 264. Given the customer's desire to have a smaller and more energy efficient machine, the specifications of the DS 264 provided an excellent place to start in terms of the team's engineering requirements and design concepts. This machine also provided the basis for many of the team's initial decisions because the market and quantity of published research for glass cutting machines is extremely limited. The DS 264 is one of a very small number of machines available and the team has direct access to the machine at all times.

The DS 264 and its current settings and set up provided a basis for our engineering requirements. Some of the metrics that the team changed to fit the description of our new machine were power consumption and number of cuts. Considering that the scope of the project was to produce a more energy efficient machine, our goal was to improve these metrics. There were also many specifications the team decided to keep unchanged. Due to the fact that there is very little published research about the physics of glass cutting, the team initially elected to mimic the performance of the DS 264 as closely as possible. This meant that the team aimed to produce a machine that would have the same roller diameter, cutting speed, roller acceleration and deceleration, stroke length, and wire tension as the DS 264. This would ensure a familiar machine set up that is known to work well.

One of the biggest challenges that arose during research and benchmarking was the general lack of available knowledge about glass cutting. The lack of published research, as well as the complexity of the DS 264, led to several technical questions that the team struggled to answer. Some of these included figuring out where the largest amount of power was being consumed, why there was cooling in the system, and how the wire tension changes during cutting. These questions were all well beyond the team's theoretical knowledge. However, starting from first principles the team was still able to develop a good qualitative understanding of what will happen during the cutting process. This thought process was confirmed by consulting subject matter experts.

While developing several design concepts, the team ultimately opted for simplicity wherever possible. Given the uncertainty in the problem and fact that the team believed the DS 264 was over engineered for Glass Fab's application, the team decided to strip out any unnecessary features, such as cooling the system and pressurizing the bearings. Instead the focus was targeted on developing a system that would allow for maximum precision in aligning and rotating the rollers to ultimately deliver accurately cut parts.

Controlling mechanical motion with electronics could be done in several different ways. There are three typical approaches that are taken in order to succeed in finding a viable option to control a system. The first approach is to create a custom made controller, which can vary widely in size and complexity. This could be anything from a printed circuit board with some operational amplifiers that allow for the basic functionality of a closed loop system (such as a summation or comparator block), to a custom manufactured controller with far more advanced computational power. The second option is a micro-controller. A microcontroller is a device that can receive analog and digital inputs and send digital and analog outputs using typically $12V_{in}$ for power. It contains a processor core as well as memory. This is an easy solution for small control systems with only a few simple inputs to be monitored. The third solution is a Programmable Logic Controller (PLC). A PLC is a larger controller than the microcontroller containing a much larger processor core, more memory, and uses an industry standard for programming the inputs and outputs. A PLC also comes with modules that allow for easy integration in control systems. When deciding which path to walk when deciding the control system needed in this system, it is important to look at what is being controlled. In the system at hand, the two rollers will have their motion profile controlled, certain temperatures should be monitored, and the system must be able to integrate with the 2 other teams. The biggest restraint for deciding the controls of the system is the speed and torque of the motor. Depending on the power required for the system, the controls scheme will reflect the needs of the system.

The frictional torque values were calculated based off of the DS-264 motor torque ratings, which were 500 Nm. From there, the DS-264 roller inertia 1.664 $kgm^2$ was subtracted at the measured acceleration of 2 $m/s^2$. Dividing the result by the approximate 4100 cuts provided a frictional torque of 0.12 Nm/cut. Since the desired system should be capable of 300 cuts by request of the customer, the resulting friction was calculated to be about 35 Nm. The motor was selected to have a continuous torque rating equal to the frictional torque since the torque due to inertia would only appear during acceleration, which is a small portion of the full motion profile.

First Iteration of the design:

Now that we felt comfortable with the amount of benchmarking we had done and the knowledge that had been gained, we began the design process. We started with a whiteboard session during which team members brainstormed ideas and improvements openly. What was previously mostly in our heads quickly evolved into a well-developed initial model. The overall design was inspired by the Meyer Berger DS 264, since most of the benchmarking was done off of this machine and the design is known to perform well. The finer details were tailored to our specific customer requirements, engineering requirements, and machine footprint. This whiteboard session proved to be extremely productive. As it turned out, the final model for this iteration looked incredibly similar to what we had on that whiteboard months earlier.

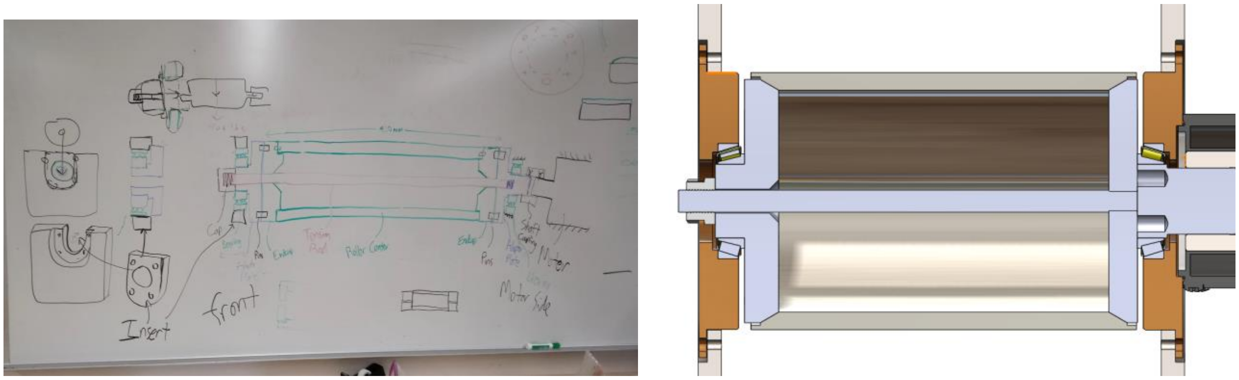


**Figure 2:** Initial whiteboard drawings vs final first iteration model cross sections

The center of this design was the roller, which was made from a hollow stainless steel tube and two endcaps. A tension rod was used to pull the two endcaps inward against the roller and bring the rollers into alignment. Tapered roller bearings were the interface between the endcaps and removable insert plates. Removing one insert plate allowed for the rollers to be removed or installed. The motors drove the motor side end caps directly, allowing the rollers to move synchronously. The most important parts in this design were the roller endcaps. They were permanently attached to the insert plates, not the roller like on the DS 264. The 60 degree taper on them functioned as a very precise locater for the rollers. The operator could easily install the rollers while consistently and accurately aligning them. The tension rod was designed to generate the force necessary to keep the endcaps tightly pressed to the rollers, ensuring that the alignment was maintained. The tension rod also pulled the roller into a consistent and repeatable axial location. This ensured that the grooves in the rollers would always be lined up precisely with respect to each other and the wire traversing from the top of one roller to the other would be straight, resulting in a quality cut.

This design received accolades and approval from the customers and guides. However, once it came time to purchase parts, the stakeholders got cold feet. This system had the capability to produce high quality parts, but one of the goals of this project was to simplify the machine. Glass Fab does not necessarily need such high quality parts. They were worried that some of the parts, especially the tapered end caps, would be too expensive and difficult to manufacture. They wanted to see us simplify the machine even more.

The electrical system differed in the decision process for approval. The decision to go with a PLC from the start was accepted, and several designs were made with different levels of capability. After drawing up the control schemes, the customer decided to go with the highest level of control design. The motor type chosen was the rotary direct drive servo motor, or Cartridge motor using Kollmorgen naming convention. This motor type is designed to be directly coupled to the load rather than through a gearbox or pulley system. With standard motors, inertia mismatch between the load and motor rotor causes undesired performance from the controls aspect. Since the smaller machine inertia was still very high at 0.8 $kgm^2$, the direct drive servo motor was chosen to negate the inertia mismatch and to simplify the guide roller driving mechanism. Originally the RDD-B21529 was chosen as the ideal Rockwell choice, but due to its unforeseen end of sales life, the Kollmorgen CH06x series motors were identified as possible replacements. This selection was verified using the Motion Analyzer software developed by Rockwell Automation. This software takes in the inputs of inertia and a motion profile and outputs a controller, drive, motor, and necessary accessories.

The electrical Bill of Materials (BOM) contains the main motors required for the machine (two guide roller motors, a take-up spool motor, and supply spool motor). It also specifies the motor cables and lengths, as well as the AC drive rack with properly sized 6500 Kinetix Drives to control the motors. Currently, the AC drive rack has eight slots. Four slots may be allocated for the guide roller motors (two per motor), two slots for the two spooling motor, and one slot for the workpiece movement team. Realistically, another 8 slot rack may be added for expansion purposes to allow for the slurry team's drives. The BOM also lists AC drive connectors and control modules. The PLC chosen was the CompactLogix L36ERM due to its support of many Input/Output (I/O) modules as well as its ability to control 16 virtual axes, which are necessary for the complex control of the many motors in the machine. Lastly, the BOM also includes a software package to program the PLC as well as Human Machine Interface (HMI) software to design a user-interface for the machine.

Final Iteration of the Design:

The final iteration of the design was a new concept created to meet the customer needs in a way that they would be more comfortable pursuing. This meant easier manufacturability of parts and simpler design solutions. Since manufacturability and the potential to manufacture parts in house was emphasized by the customer, this iteration began with a design discussion with the RIT machine shop personnel. The focus was on guide roller installation, alignment, and stability. First, gusseted angle plates were suggested on the basis that they could be very precise in flatness and alignment, provide extra support for the rollers, and can be bought as an off the shelf part. These could be precisely pinned and bolted to a baseplate that will define the footprint of the machine. It was decided to have an opening cut in the center of the base plate to allow for slurry to drop down into the tanks below. Finite Element Analysis (FEA) was conducted to confirm that the plate would still be strong enough with regards to mechanical and vibrational stress with this aperture cut into it, or that if it is not, sufficient support can be added to bring these properties of the plate into a safe regime. Next, due to the complexity of the pressure locking roller alignment design, the bearing yoke design was suggested as a drastically simpler design. It is based off of benchmarking with other machines which use a similar concept. The benefit of this concept is that the yoke can be manufactured as an individual part and bolted on to the angle plates. Then, all the seats for the bearing can be bored out from the bottom half of the yoke in a single operation, allowing for extremely precise alignment of the rollers. Following this, it was discussed that the roller, shaft, and bearing could all be a single assembly that would simply be lowered down and sit in the precisely manufactured yokes. Bearings can easily be pressed on or pulled off the roller as needed, and the roller/shaft assembly might even be more helpful for coating companies to take advantage of. The motors would still be face mounted, as in the first iteration, however motor to roller coupling had to be carefully considered to allow easy removal of the rollers. To solve this, different couplings were benchmarked and a shaft adapter was identified as a viable solution. If the rollers could be reset to a zero position, the shaft adapter would have a removable plate that is always accessible from the top. Once this is removed, the guide roller assembly could simply be lifted and removed. The next design consideration was the lower precision in roller location in the axial direction since we no longer would have a pressure locking mechanism to keep it from moving in this direction. To accomplish this, a lip was added to the motor side yoke. When the roller is lowered into the yoke seats and clamped in, the motor side bearing will be locked tightly in place given a high tolerance lip gap. This will bias the axial location of the roller to the motor side, and therefore position the rollers to within a tolerance of whatever axial motion is allowed in the bearing races themselves. This was decided to be tight enough for the purposes of this simpler design. Finally, some minor details were added to the design to meet customer requests. These included a catch tray for falling parts that could slide in and out, and a viewport for the operator to be able to see the bow in the wires during cutting. To allow for this, the angle plates were separated slightly, and sealed with a transparent polycarbonate. The catch tray design was simply based off of the DS 264 catch tray. Finally, covers for the bearing and yoke were created to prevent slurry from entering these areas, as well as a magnetic removable cover to gain access to the catch tray. The design to date can be seen in the figure below. The electrical systems did not change from the initial design iteration. Progress that was made included consulting with a 3rd party electrical engineer on cabinet design and construction, and consulting with Zeller, a commercial supplier.

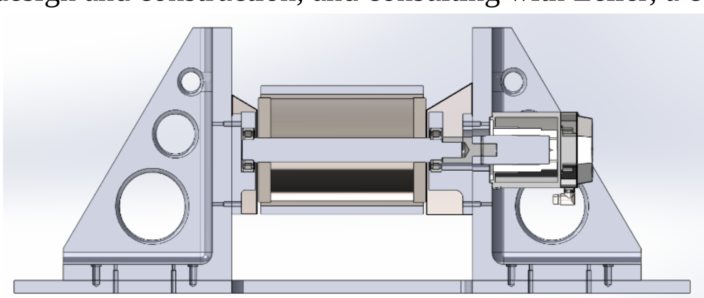

**Figure 3:** Final iteration of design cross section

<u>Current State:</u>

Our design to date is virtually complete, but there are still minor changes that need to be made and potential issues that have been addressed regarding the final design iteration. Mechanically, the design needs to be modified to take out the polycarbonate paneling being used as the viewport. With the abrasive slurry running down these panels during the cutting process, the build-up of scratches and wear will eventually make the window cloudy. Instead, Glass Fab would prefer a metal screen with an access door. Also, a new motor is still awaiting approval. With the potential for a change in motor dimensions, the shaft adapter and mounting features on the angle plates may end up needing minor modifications to create compatibility with the new motor. A full CAD model and fully drawing package are completed for the design discussed, and all potential problems have been brainstormed and tracked. A preliminary test plan document has also been started and assembly instructions defined.

The current state of the electrical system consists of chosen major electrical components with a BOM, controls architecture, and electrical cabinet concept. There is a specified BOM of electrical components for the guide roller motors. However, due to the recent discovery that the RDD-21529 motor was in its end of sales life, a quest for another motor has ensued. Promising replacements include the Kollmorgen CH06x series which are the same exact motor type, except from the manufacturer Kollmorgen. Some details that need to be verified are whether the new motors will be compatible with the Rockwell Kintetix 6500 drives in terms of encoder feedback and if the motor replacement may need a larger AC drive than previously specified due to a higher speed.

The controls architecture includes a master profile to which every motor will try to follow except for when other variables come into play. Essentially, the guide rollers will try to follow a master profile, while the spooling motors will try to follow and maintain wire tension. The workpiece feed rate will be adjusted accordingly to ensure that the wire tension is not increasing too much. A lot of controls concepts and ideas have been thought about but no real programming work has been done. The next step in the project would be to make a list of I/O and purchase the PLC with the I/O modules in order to start the programming process. Even though the L36ERM PLC can support up to 960 I/O points (analog, digital, relay, monitoring, communication modules, etc.), they need to be specified for the machine. A good amount of digital I/O will need to be used for the safety interlocks. Some analog I/O can be used to monitor the process in terms of temperature or other variables if necessary. At the very least a 16 point digital input and 16 point digital output could be purchased with the PLC to get things started.

For such a complicated system that uses 480 $V_{AC}$ motors, a major challenge has been to find someone to help with the proper design of an electrical cabinet to contain all of the AC drives and PLC. The Zeller Corporation (part of Kaman Automation) on University Avenue in Rochester, has agreed to help in the design and manufacturing of the electrical cabinet according to the student's specifications. They have entered our project into their system under the identification number 160828 and are willing to work with the students to design the electrical cabinet. The next step would be to provide them with a finalized BOM of chosen AC drives and motors with the PLC and I/O modules and add anything else the Slurry System may need as well.

In sum, the next steps for the electrical system include specifying I/O modules, starting the programming process, and beginning the cabinet construction with Zeller’s help. From here, all mechanical and electrical components need to be sent out for quotes and purchase. Ideally, during the summer of 2016, the full fixture will be assembled by the Glass Fab team.

Throughout the entirety of the design process, we have continually updated a series of documents tracking our work. One of these documents is a problem tracking form. In the beginning of our design, this was referenced as a "risk assessment" form. As the inherent risks of a clean sheet design came to fruition, we formed the problem tracking document to determine the best possible ways to mitigate any risk and assigned an engineer as the owner to provide accountability in solving each problem. We also created a growing bill of materials (BOM) for the electrical components and the mechanical components. The electrical BOM contains the controls for all three systems to prevent over-purchasing components that could, eventually, be used together. The mechanical BOM contains all parts for the individual fixture, ranging from custom manufactured parts to parts that have been sourced for purchase from Grainger. Both BOMs are comprehensive lists of every part required to assemble the final machine.

In order to simplify the purchasing process, the systems engineers created a purchasing process in collaboration with Glass Fab's head of purchasing, Lori. A full plan was established from design approvals to part procurement. This purchasing flow chart was produced as the initial design was coming to completion, so it took time to work out some kinks. Ultimately, no parts made it fully through the purchasing process, but this will become beneficial as future teams begin ordering.

Project Downfalls:

The successes of this project did not come without its fair share of obstacles. The biggest challenge to our team was rooted in a lack of commitment from our stakeholders, including our customer and the machine shop staff. In the beginning of the project, it was difficult to get in contact with Glass Fab in order to ask their opinion on major design decisions. Whether it was an unanswered phone call or no response to an email, we were left to make critical design decisions without customer approval or input. Although these design decisions were backed by pugh charts, benchmarking, and theoretical calculations, the customer could always put in a countering opinion at any time. This led to wasted time and work, which quickly became a frustrating situation for our team. Lack of communication between the team and the customer was evident during design reviews as well. Glass Fab joined us every three weeks to review all changes that had been made since the last discussion. Overall the feedback was very positive and thankful, but little criticism of any design was brought to the table. The details were frequently overlooked, leaving us unaware of whether or not the machine we were creating was exactly what Glass Fab wanted. These communication issues were resolved in the second semester, when it was decided that the systems engineers would send one comprehensive email a day, with a promise to get information back in the following one to two days. Additionally, our team began to work directly with Ray, the machine operator, to explain exactly how parts would be used in detail. This allowed him to provide feedback on the level of complexity each design change would add to his job, as well as what additional design changes he would like to see on the machine.

Another stakeholder that showed a lack of commitment was the machine shop. The shop was able to provide a big-picture critique of our designs through MSD I, but not to the degree necessary for the precision manufacturing required for this type of machine. When it came time to begin purchasing, the machine shop staff began to notice that this project required significantly more attention than it had previously been given and began to deeply review our drawings. After a long meeting, the team and the machine shop came up with the concept for the final iteration design discussed earlier in this paper. If these stakeholders had been involved sooner, we may have had our design changes completed in a timelier manner and been able to purchase parts. After this meeting, the machine shop remained involved in the design process and approved all final changes. Overall, the lack of commitment and communication from our stakeholders caused a significant amount of wasted work and time, which brought team morale down at times. Fortunately, solutions were formed and the design was able to be completed and approved by all.

A separate major downfall of this project was that the scope of the project was drastically underestimated. The original project readiness package indicated that we would be one of three individual fixtures, implying each would be able to work independently of each other. We quickly learned that this would not be the case because each system is highly dependent on the next, and the cost of each fixture would be too high to allow for the design and manufacture of parts that might not transfer to the end state product. As the center of the machine, a lot of the integrating features fell on our team. This meant that our team frequently changed design to accommodate other teams, even if the others had not begun their design. The constant changing of other designs placed a burden on our team, but we continually adjusted and provided the centerpiece of the machine that was required. Additionally, we learned early on that the original budget planned for our team would be difficult to keep. The electrical components, specifically, cost significantly more than expected. When the quotes from the electrical equipment began coming in, it truly put the scope of the project into perspective. This misunderstanding caused our project to remain in the design phase through MSD II, preventing all teams from seeing the build of our final project. In the end, we produced a successful design but did not get to see it through to completion.