Final Design Report for an Automatic Diffraction Grating

Sponsored by Dr. John Ridgely and Dr. Russ Genet
Funded by CP Connect

June 2015

California Polytechnic State University, San Luis Obispo
Mechanical Engineering Department

Team StarT.E.K. :
Tim Jung
Edlin Garcia
Kelly Rorden

Statement of Disclaimer

Acknowledgments

Special thanks to Dr. Peter Schuster for being an excellent Sr. Project Advisor. We have all gained an immense respect for you as an Engineer and professor at Cal Poly.

Special thanks to Dr. Russ Genet and Dr. John Ridgely for sponsoring this extremely interesting Sr. Project.

Shout out to the incredibly awesome team StarT.E.K.. Kelly and Edlin you are two of the best friends that anyone could ask for.

Tim you are kinda awesome too.

Special Thanks to CP connect and Cal Poly for funding this project.

Table of Contents

Executive Summary

The purpose of this report is to describe the design and manufacturing specifications for an automatic diffraction grating system. To the best of our knowledge, this system is a unique design that has never been seen before, and is the first of its kind to attempt to be autonomous. This apparatus is designed for Dr. Russ Genet's Celestron C-11 telescope and a prototype of the system was constructed. The project was designed to have most of its parts be off the shelf and adjustable so that it can be easily replicated.

The grating system is used to diffract the incoming light from binary star systems and create a pattern on the lens of the telescope. The pattern is then used to analyze the distance and angle between the two stars. The system consists of a stationary chain belt that interacts with a geared carriage to rotate the grating around the outer diameter of the telescope. The grating is attached directly to the carriage and uses a scissor mechanism to adjust the width between the gratings. There is also a feature that flips the entire system off of the face of the telescope lens so that the telescope can be used without interference by the grating. The system is designed to be controlled remotely from a warm room; therefore the entire system adjusts automatically when a star system is selected.

Team StarT.E.K.-(From Left) Kelly Rorden, Tim Jung, Edlin Garcia

Chapter 1: Introduction

Introduction

While a number of precision instruments exist for measuring the position angle and separation of binary stars, one of the simplest, yet effective instruments is the use of a diffraction grating. The shape of the diffraction grating device may vary, but their purpose is to produce a series of images that can be used to find the orientation, position angle, and separation between binary stars. Currently, the type and spacing of the grating used must be manually adjusted in order to produce the best results with various types of stars. Although this method gives good results, there is currently a need for a semi-automatic diffraction grating system in order to analyze a wide variety of binary star systems in one sitting. An automatic system would increase the rate of analyzing one binary star systems in several hours, to roughly 40 star systems in just one hour.

Team StarT.E.K. of the California Polytechnic State University, San Luis Obispo, has been contracted to design a "Semi-Automatic Diffraction Grating." The team is comprised of three members: Kelly Rorden, Edlin Garcia, and Tim Jung. The project is sponsored by Dr. John Ridgely, a professor at Cal Poly San Luis Obispo, and Dr. Russ Genet, a research scholar in residence at Cal Poly San Luis Obispo. The scope of this project is to design a system that autonomously adjusts the diffraction grating of small scale (10-11in) telescopes based on user or computer inputs. This will allow the telescope to measure the position angle and separation of binary stars, which in turn allows astronomers to determine multiple other characteristics.

The goal of this project is to design a system that is compatible with standard astronomical telescopes and can be mounted on Dr. Genet's Celestron C-11 telescope. Our mounting system is designed to attach to a range of telescope sizes, without modification. The system has been designed such that a given binary star system will be input, and once the telescope has oriented itself, the diffraction grating can be remotely adjusted in order to properly examine the system. If time permits, we intended to design the system to analyze the images obtained autonomously as well. This is not a design requirement, but would be a definite perquisite.

The development of this design will help astronomers learn more about the vast universe around us. An automatic diffraction grating will allow astronomers to discover more binary stars and determine the mass of each using advanced calculus. The goal is to develop a database with characteristics of each known star in outer space, so that we can use that information to understand more about the nature of the universe. An important step forward in this endeavor, is the development of a semi-automatic diffraction grating.

Sponsor Background and Needs

Sponsors

The sponsors of the automatic diffraction grating system are Dr. Russ Genet and Dr. John Ridgely. Dr. Genet is a Research Scholar in Residence at California Polytechnic State University, Adjunct Professor of Astronomy at Cuesta College, and Director of the Orion Observatory. He works closely with Cal Poly and Cuesta students to assist in research and development of astronomical advances. Dr. Ridgely is a mechanical engineering professor at Cal Poly with a special interest in mechatronics and robotics. He has his PhD in Mechanical Engineering and his thesis was on design and simulation of running robots. Both sponsors are passionate about advancements in technology and astronomy and have been very involved in the design process.

Funding

The target cost for producing the final prototype was $400, this amount has since doubled and a detailed cost analysis can be seen in Chapter 4. The project was initially going to be funded by our sponsors, but as of November 12, 2014, additional funding was confirmed and was provided by CP Connect for up to a total of $2,074.75. This funding was used to supply materials for the prototype, testing and research.

Formal Problem Definition

The astronomical study of binary stars is often hindered by the difficulty of collecting differing types of data using the limited number of methods we have for observing stars. In order to obtain additional information about the type and motion of binary stars, a diffraction grating is often used. This diffraction grating bends the incoming light from the binary star system, allowing for the observation of individual stars.

Currently, there is a need for a semi-automatic solution for the use of a diffraction grating in an astronomical setting because the current system is controlled by hand and can take several hours to analyze a single star system. This automatic diffraction grating system would need to be affordable and usable by the general astronomy community, and would be compatible with current telescope automation software and technology. Ideally, the system would be capable of adjusting through a full range of motions: rotating 360 degrees, and adjusting in width and spacing. The system would be required to be easily mountable to Dr. Genet's Celestron C-11 Telescope, and would have to be lightweight enough not to greatly hinder the automated tracking systems that are already present. This project aims to design and prototype an automatic diffraction grating system that meets all of these requirements, and that is both an asset to astronomers, and a benefit to science.

Objective and Specifications

The overall goal for this project is to create a diffraction grating that is adjustable and can be controlled remotely. The following is a list of specific design requirements and product specifications developed from the given customer requirements. A full summary and discussion of the customer requirements can be found in the Customer Requirements section.

Customer Requirements

As stated by Dr. Ridgely, the desired outcome for this project is to design and prototype an automatic diffraction grating system that can be easily mounted to telescopes ranging from 10-11 in diameter, and can be used with existing telescope software. This grating system would need to be adjustable in width to provide a variety of diffraction patterns, and would need to be rotatable through 360 degrees to be able to diffract an image in any orientation. The system may either have adjustable bar widths, or have interchangeable gratings that are switched in and out. The weight of the entire diffraction system is also required to be lightweight as an excessive amount of mass would significantly affect the existing telescope tracking and automation systems, by causing oscillations, stressing actuators, and hindering motion. The specific customer requirements as given are listed below.

- Compatible with Dr. Genet's Celestron C-11 Telescope (11 inch diameter).
- Grating must rotate through a full 360 degrees, with an accuracy of ± 1 degree.
- Optical transmissivity λ/10.
- Compatible with ASCOM and/or INDI software.
- Adjustable in width and spacing up to 5x its smallest size.
- Semi-Automatic.

In addition to the specific requirements received from Dr. Ridgely, there are several desired features that we have identified for this project:

Safety: It is desirable for the automatic diffraction grating system to be quick and simple to handle, install and use. A major component of this is designing the grating to be safe enough to handle with one's bare hands. To this end, the final design should free of sharp edges, pinch points, open circuits, and other safety hazards.

Speed: Because this system is intended to run automatically or semi-automatically, taking measurements of a large number of stars per night, the diffraction grating must be able to operate quickly enough so as not to significantly slow the operation of the telescope. It must also be quick enough that there are no delays when using the system for individual tasks.

Environmental Conditions and Durability: As a system intended for use on high end amateur telescopes as well as scientific telescopes, it is reasonable to assume that the diffraction grating will need to perform in outdoor and non-controlled environments. To this end, the Automatic

Diffraction Grating is required to be capable of withstanding mild temperature, dust, and corrosive environments.

Ease of Use: It is assumed that the system may be used by people of varying ranges of expertise, so it is important to make sure that its basic operation can be learned in a reasonable amount of time by both experts and non-experts.

Continuous Run Time: As this has the potential to become a fully automated system, it is a reasonable requirement for it to be able to function without assistance or maintenance for an extended period of time. This would allow for increased productivity, as well as a further enhancement of the data collected.

Beginning with the initial list of customer requirements, we proceeded to develop a list of engineering specifications. This provides us with specific performance goals that we can design for, as well as benchmarks that we can use to verify our prototype's functionality and performance through testing and analysis once it has been built. The QFD (Quality Function Deployment): House of Quality diagram has been widely used in industry, and has proven to improve the quality of product design in many companies including large, well-known ones like Toyota. Because of its efficiency, we decided to use this method to develop the engineering specifications needed for this project.

The QFD diagram is a comparison chart where one can analyze the who, what, how, and now aspects of our problem statement and can be found in Appendix A. The "who" refers to the potential customers or users, the "what" lists their needs, the "how" specifies how the designer will verify if the product met all of its requirements, and finally the "now" lists other products currently on the market with the same functionality as the system being designed. Each of these categories are listed on a side of the diagram, and they are compared or ranked against each other. This allows the designer to see how their potential system ranks against current devices and shows how categories affect one another, thus providing a form of reference as to what to avoid or look for when coming up with a possible solution that will address each specification. Each customer requirement must corresponds to at least one engineering specification, and once these are defined, a target number for each is assigned so that performance analysis of the system can be carried out based on this reference value.

Based on our knowledge and research about the environmental conditions that our device will be exposed to, as well as the varying hardware and software components that it will interface with, we came up with a list of engineering specifications that correlate with our customer requirements. In our case, each customer requirement was able to be addressed by at least one engineering specification, except for one: the appropriate blade requirement. Another component of the diagram which could not be fully explored was the comparison between our possible device against current systems. Since this project focuses on a possibly recent and innovative idea, no automatic diffraction grating systems have been discovered on the market, so the only current competition is manual diffraction grating systems. Each engineering specification has a corresponding target number that was obtained either directly from our

sponsor, or implied and interpreted from the given requirements. Having a target goal for each engineering specification will ease our design analysis and testing phase, allowing us to find the appropriate make the appropriate changes and modifications to the system to better address the given requirements.

Discussion of Specific Engineering Requirements Specifications

The engineering specifications developed from general customer requirements or desirables are summarized in table 1.

The risk rankings are listed as “High”, “Medium”, and “Low”, signifying the level of risk that a product will be unable to meet this requirement.

Table 1. Engineering Specifications Target Values

Spec. #	Parameter Description	Requirement or Target	Tolerance	Risk	Compliance
1	**Angular Accuracy**	± 0.1°	Max	M	T,A
2	**Weight**	10 lbs.	Max.	L	A,T,S
3	**Rotation**	360° or 180°(with Symmetry)	± 1°	M	A,T
4	**Speed**	< 10s	Max.	M	A,T
5	**Software Compatibility**	ASCOM, INDI		L	S
6	**Cost**	< $400	Max.	M	A
7	**Adjustability of Bar/Gap Width**	1:5 ratio, 0.25-1.5"	± 1%	H	A,T
8	**Diffraction Functionality Test**	ADS Simulator Designed by David Rowe	Various Patterns	H	T
9	**User Input Required**	None/Semi-Automatic		L	I
10	**Mounting**	10-11 in (Telescope Diameter), Adaptable to Larger Models		L	T
11	**Environmental Conditions**	0-50°C, Fog, Corrosion	± 5°C	M	A,T
12	**Overall Size**	20H x 75D cm	Max.	L	A,I
13	**Safety**	No sharp edges, open circuits, pinch points		L	I
14	**Ease of Use**	Learn basic operation in 30 min.	Max.	L	T
15	**Optical Quality of Transmission**	λ/10	Min.	M	A,T
16	**Continuous Runtime**	10 hrs. (with input)	Min.	M	A,T

(Compliance key: A=analysis, T=testing, S=similarity to existing designs, I=inspection)

In addition to the specification and engineering tolerances assigned to each category, each function is assigned a risk rating, as well as one or more flags to categorize the type of testing that will be required to verify this function. For example, an Inspection flag signifies that the product will simply need to be measured or visually inspected, whereas an analysis flag indicates that data acquisition and calculations will be required in order to verify if the product passes or fails.

Weight: As other components within a large telescope assembly can weigh upwards of 60 lbs., (Obsession Telescopes) the addition of a 10 lb. weight to the end of a telescope - and a matching counter weight if needed - will not be enough to significantly hinder the automated telescope tracking systems.

Rotation: Provided that the diffraction grating has at least one axis of symmetry, it is only necessary for the diffraction grating to rotate 180° degrees, instead of a full 360°.

Speed: In order to prevent significant delays between capturing images with different diffraction patterns, the Automatic Diffraction Grating should be able to transition between any two positions within 10 seconds. This time is significantly faster than the time it would take to manually adjust or swap out a non-automated diffraction system, and would not present a significant burden to the user.

Software: Dr. Ridgely has stated that two of the commonly used open source software packages are ASCOM and INDI. The Automatic Diffraction Grating would be designed to be compatible with both of these software packages.

Cost: Both by request of the Customer, as well as comparison to an entry cost of approximately $4,000 for a high quality 11" diameter telescope, $400 is the target cost for a competitively priced model that at 1/10th of the price of the full telescope, is not an overpriced accessory. Since the prototype is expected to cost more than a production model, we will aim for the initial prototype models to cost approximately $400, and still allow for a potential margin on any future production designs.

Chapter 2: Background

Prerequisite to the design and construction of an Adjustable Diffraction grating is the understanding of several areas of research. The first area of research is the study of binary stars. Unlike the lone light source in our solar system, binary stars orbit each other around a common center of gravity. While this system may seem more complex than a simple single star, the relative orbits of each binary star allows us to determine a number of properties that would otherwise be impossible to acquire. Secondly, the science of using diffraction gratings to examine binary stars has history stretching back centuries (Argyle). Any successful design for creating an automated diffraction grating must be based on the science and function of a manual diffraction grating. Finally, in order to create an automated system that is of actual use to the scientific community, the system must be able to interface with existing telescope and telescope software systems. For our purposes, we will be interfacing our system with Dr. Genet's Celestron C-11 telescope. We will be using his telescope to test and implement the Automatic Diffraction Grating project.

Binary Stars

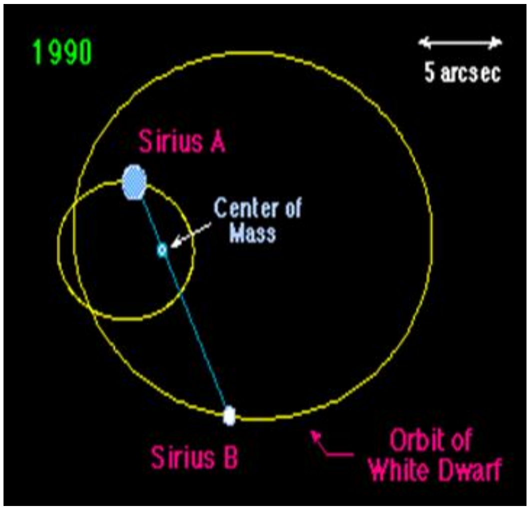


Figure 1. Binary Star Orbits (Visual Binaries, 11/12/2014)

It is estimated that more than 50% of the stars in the universe are multiple stars, which makes it difficult to see each star individually as they overlap. Multiple stars can either be optical doubles or binary stars. Optical doubles are two stars that lie in the same line of sight. Binary

stars are two stars connected gravitationally and orbit each other. Binary orbits typically have elliptical paths that range from shorter than one year, to a millennia (Jaworski).

Binary stars can be further categorized into four types: visual binaries, spectroscopic binaries, eclipsing binaries, and astrometric binaries. Visual binaries have a wide enough separation that they are both visible by telescope, where spectroscopic binaries appear too close to distinguish even when viewed through a telescope. In order to analyze them, one must use measurements of the wavelengths. Eclipsing binary stars are two stars whose orbits are at an angle to each other, so that from earth one star passes in front of the other, causing an eclipse. Astrometric binaries are stars that “dance” around an empty space because their companion cannot be identified, only inferred (Binary Star Systems: Classification and Evolution). Because visual binaries are easier to identify, they are of great interest to astronomers.

When observing binary star systems, the brighter star is known as the primary star, and the fainter star is known as the secondary star. The position angle of a binary star system is the position of the secondary star, b, as reckoned from the primary star, a. As seen in Figure 1.0, the angle is measured from zero degrees due north and rotates counter clockwise (East=90°, South=180°, West=270°). Note that east is actually to the left of North, because you are looking up at the sky, rather than down at a map.

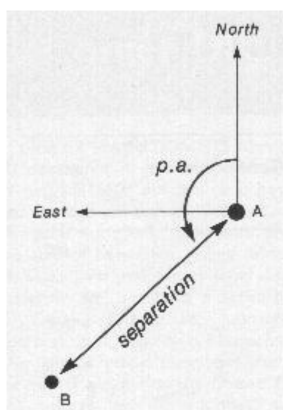


Figure 2. Binary Star Position Angle Diagram (Jaworsky, 10/18/2014)

Before you can measure the position angle, you have to determine how the system is oriented on the North/South/East/West plane. In order to do so, the observer must let the binary star system drift across the camera. The stars will move East to West and then you can determine the East/West axes, and North/South are at right angles from those axes. We will be using diffraction grating in order to measure the position angle and separation of binary stars (Jaworski).

Diffraction Gratings

Using the simplest terms, light bends when it passes through a slit or around an edge. This bending is called diffraction. As the light bends, it creates a diffraction pattern which is the pattern of light and dark satellite images caused by the interference of wavelengths. A diffraction grating is a compilation of several slits that light is projected through, creating an array of satellite images on both sides of the light source in a line perpendicular to the grating slits. The central image is usually the brightest satellite of the array and is known as the zero-order image. The neighboring satellites are the first-order images and the satellites next those are the second-order and so on. Generally, only the zero and first-order images are taken into account when analyzing a binary star system because that is all that is needed to determine the characteristics of the star system. The distance between the satellites is based on the separation of the slits and the wavelength of stars' light. If the wavelengths of the bent light are in phase, their wavelengths will sum together and create bright responses. If the wavelengths are out of phase they will subtract from each other and create dimmer responses. If the wavelengths are 180 degrees out of phase, no light will be emitted at all, which causes the dark spaces between light responses. Figure 2 demonstrates the diffraction produced by a diffraction grating.

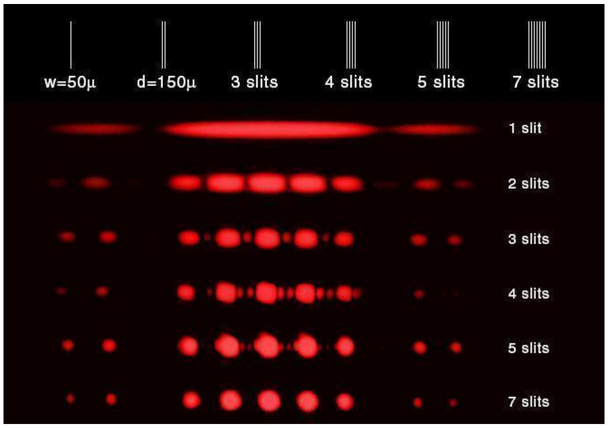


Figure 3. Examples of Arrays of Satellite Images Obtained from Shining a Laser through Various Diffraction Gratings (Diffraction and Interference, 10/31/2014)

The separation of the slits are very critical because the distance between the zero and the first order image depend upon the slits and the wavelengths of the stars' light, and the distance between the two orders are used to find the position angle and separation of double stars. According to the book, *Observing and Measuring Visual Double Stars*, experience has shown that gratings where the width of the bars are equal to the space between bars gives the best results because it corresponds to the maximum brightness of the first-order images. The critical dimension of a diffraction grating is the slit distance, *p*. The slit distance is the sum of the

grating slit width, L, and the bar width, D. The angular separation, Z, of the binary star system which is measured in arc seconds can be determined by the following equation:

$$Z = \frac{206{,}265\ \lambda}{(L\ +\ D)} \tag{1.1}$$

Combined with the diffraction equation:

$$(L + d)(sin\theta_1 - sin\theta_i) =\ \lambda \tag{1.2}$$

Where, L and D are in mm, and Z is the wavelength of starlight in mm*arc seconds. The constant in the numerator is the numerical conversion from radians to arc seconds. In practice, astronomers usually use a set of four gratings, whose slit distances are 10, 20, 30, and 40 mm. The grating itself can have various slits, but is more effective if there are fewer bars (but at least three) because that results in more satellite images, as well as brighter images.

Figure 4.Diffraction Grating on an Astronomic Telescope (Argyle, 11/01/2014)

Types of Telescopes

The three types of commonly used telescopes are the reflecting, refracting and the catadioptric telescopes. The reflecting telescope relies on a series of mirrors arranged to focus and form an image, while the refracting telescope accomplishes the same task using optical lenses (Figure 4, 5).

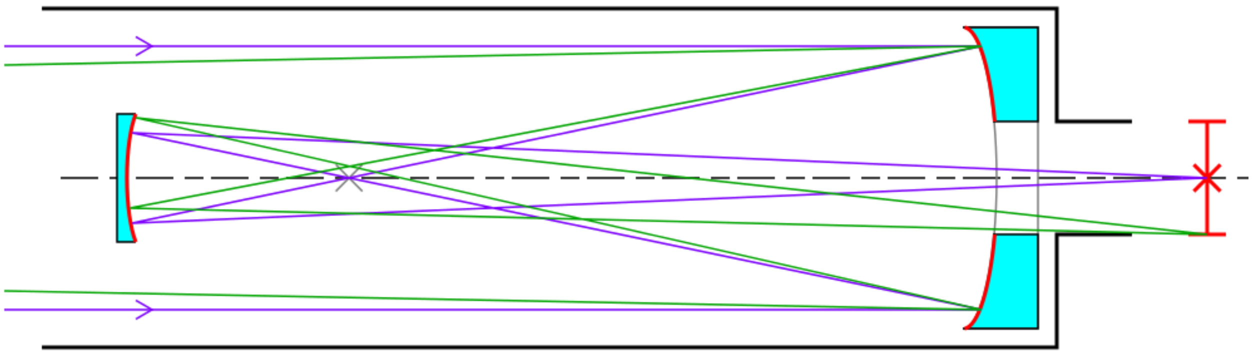


Figure 5.A Gregorian Reflecting Telescope, with Blue and Green Lines Representing the Path of Incoming Light (Gregorian Telescope, 10/21/2014)

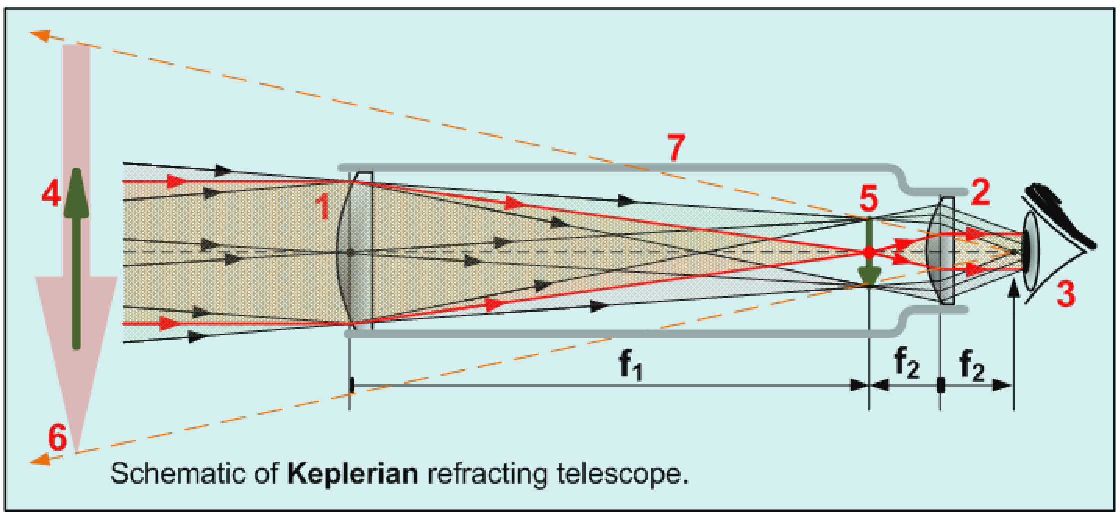


Figure 6. Schematic of a Refracting Telescope (Kepschem Refracting Telescope, 10/21/2014)

The catadioptric telescope combines both the reflecting and refracting telescopes using both shaped mirrors and focusing lenses to form an image. We do not believe that these different telescope configurations will affect the functionality of the diffraction grating, however further testing and research may be required.

Two main types of telescope chassis exist: The first type of chassis, known as the "SCT" design, encases the entire focusing assembly within a single tube. This makes for a compact and easily adjustable telescope that can operate without being confined to a controlled, clean environment. The downside of this design is that the single walled tube that typically forms the main chassis is difficult to physically modify. This difficulty restricts mounting points to external additions on the body of the telescope. Another common chassis system used with telescopes is the "Open Frame" approach (Figure 6). Instead of enclosing the telescope's array of lenses

and mirrors within a solid tube, a minimal truss system is used to align the telescope's focusing system.

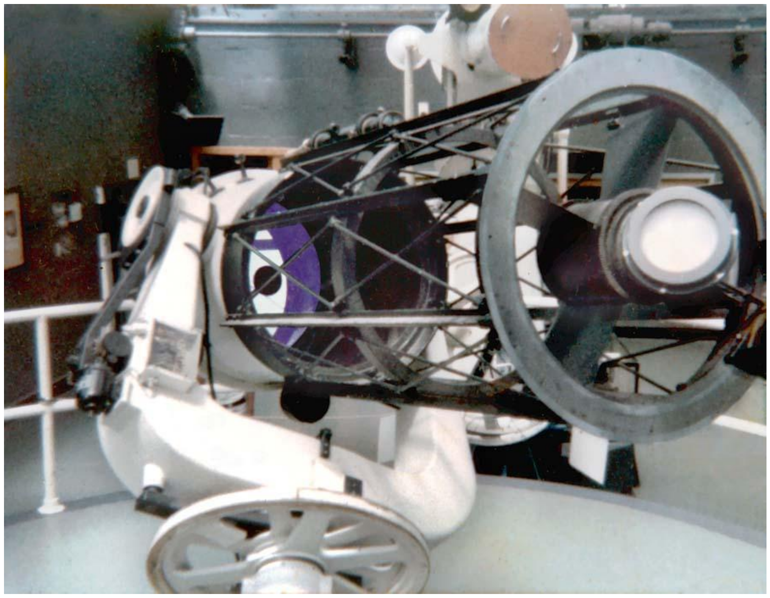


Figure 7. . An Open Frame Telescope (Franklin Reflecting Telescope 10/26/2014)

While these open frames can be cheaper, easier to construct, and more lightweight than SCT style telescopes, the internal focusing lenses and mirrors are exposed to the surrounding environment, making open frame style chassis less than ideal for outdoor environments. The open frame chassis is however, an ideal system for adding custom mounts. Since the frame is open, non-critical to the focusing array, and structurally tied to the rest of the telescope, creating a custom mounting point can be a simple procedure. On the other hand, since there is some variety in the specific structure of open frame style chassis, creating a uniform mounting system could prove to be difficult. The initial testing and prototyping will involve SCT telescopes because that is the type of telescope that Dr. Genet owns.

Orion Observatory

The telescope that we will be mainly using for testing purposes and basing our design on, is located at the Orion Observatory. The Orion Observatory, founded by one of our sponsors, Dr. Russ Genet, is located in Santa Margarita, California, an approximately twenty minute drive from Cal Poly. At the observatory, one can find a Celestron C-11 Schmidt-Cassegrain Telescope with an SBIG ST7 CCD camera that works with software bisque CCD Soft, The Sky, and Excel VBA analysis. The Celestron C-11 is a catadioptric telescopes. One of the studies that has been conducted at the observatory relates to overcontact binaries. Overcontact binaries are stars

that come in pairs and coexist in physical contact. They revolve around each other through a period of time that can range from six to eight hours, and as they take turns eclipsing each other, their light intensity varies. Through overnight data collection, the system of contact eclipsing binary stars is analyzed every minute to produce a light curve of brightness versus time. (Orion Observatory and Russ Genet.)

Figure 8. Celestron C-11 Telescope (Orion Observatory and Russ Genet, 10/17/14)

The Celestron C-11 Telescope mount and all electronics are internally powered by batteries, which usually operate the telescope for about twenty hours, more than enough time for these studies to be carried out throughout the night. (LX200-ACF 10" F/10 with Standard Field Tripod.)

Software

Two of the commonly used types of astronomical software include ASCOM and INDI. They're both open-source software available for telescope control systems, and they are compatible with the C-11 telescope. ASCOM and INDI have the advantage of being able to have the source code modified in order to properly work in different environments. ASCOM is compatible with a wide range of languages and it can be run on Microsoft Windows 7, Vista, and XP. It works on both 32- and 64- bit systems, but it is not supported by Windows 2000. In order for ASCOM to work with The Sky, one of the different kinds of software that the C-11 works with, adapter components have to be installed to make them compatible. (ASCOM - Standards for Astronomy.)

Patents

We were aware that this project is a very recent idea that astronomers would like to try, so we knew that it would be hard to find similar products out in the market. However, we decided to investigate if there were any patents out there that either served a similar purpose, or that looked similar to what we were about to design. As expected, not many patents were found. As seen in Table 2, most of the results that we obtained from the United States Patent and Trademark Office (USPTO) website, showed patents for systems that were part of the lens, or not externally attached to a telescope like the diffraction grating system that we are designing. Additionally, they tended to be geared towards smaller scale apparatus. Most patents also seemed to be recent, the oldest was from 1994, and the most recent was from December 30th, 2014, which was just as we were planning our design. As we continued with the patent search, we also found that the studies or development of diffraction grating mechanisms were also very popular in Japan. The following table shows a few of the patents that were found on USPTO and which have some relationship to the system that we were required to design.

Table 2. Current Diffraction Grating Patents in the U.S.

Name of Patent	Patent Number	Date of Patent	Inventor (s), Origin
Diffraction Grating Device, Laser Diode, and Wavelength Tunable Filter	US 8,040,933 B2	October 18, 2011	Takashi Kato, Yokohama (JP)
Diffraction Grating Lens & Method of Producing the Same, and Imaging Device in Which the Same is Used	US 8,649095 B2	February 11, 2011	Takamasa Ando, Osaka (JP) Tsuguhiro Korenaga, Osaka (JP)
Lensless Imaging with Reduced Aperture	US 8,693,001 B2	April 8, 2014	John Farah (US)
Diffraction-Grating Photopolarimeters and Spectrophotopolarimeters	5,337,146	August 9, 1994	Rasheed M.A. Azzan, Metairie, LA
Spectroscopic Measuring Apparatus with Monitoring Capability	US 8,922, 762 B2	December 30, 2014	Toshio Yamazaki, Tokyo (JP)
Spectral Analysis Unit with a Diffraction Grating	US 7, 852 ,474 B2	December 14, 2010	Hans-Juergen Dobschal, Kleinromsteadt (DE) Ralf Wolle Schensky, Jena (DE) Wolfgang Bathe, Jena (DE) Joerg Steinert, Jena (DE)

Chapter 3: Design Development

The development of a refined system capable of fulfilling all of the requirements for the adjustable diffraction grating is a careful and involved process. To this end, team StarT.E.K. has approached and analyzed the adjustable diffraction grating project with a series of careful ideation and evaluation processes. Initially we held ideation sessions, whose sole purpose was to come up with as many design possibilities as possible. We then, used the design specifications and requirements detailed in chapter 1 to evaluate our initial designs. Next we performed detailed analysis and preliminary testing to ensure that our conceptual designs are sustainable. These processes and their results are summarized below.

Ideation and Development of Initial Designs

After establishing the specific customer requirement, the next step in the development process was to begin inventing and listing the possible solutions. These ideas were typically focused on one of the three functional categories of the Adjustable Diffraction Grating system: grating, mounting, and rotation.

Because no automatic diffraction grating system currently exists, there are very few designs to evaluate or compare to. In order to overcome this, a particular effort was made to develop as many ideas as possible. Not only does this allow for a greater number of possible successful designs, it increases range of ideas and possibilities that have been covered. These two factors help us to conceive and select the best design possible.

During the ideation process, there were four main areas that were pursued. First, we sought to find as many new approaches as possible. Specifically, new mechanism designs, alternative movements or motions, or non-typical methods for obscuring light were considered. Secondly, the repurposing of existing technology or devices was considered. Optometrist’s lenses, connect 4 games, and slide projectors and more devices were all considered. Next, advanced technology was considered. For instance, an LCD screen that could digitally form diffraction grating images was considered for quite a time. Finally, completely unique ideas were considered. Custom film strips, expandable materials, or stacking lattices are all ideas that fell into this category. Our ideation sketches can be seen in Figures 9-13.

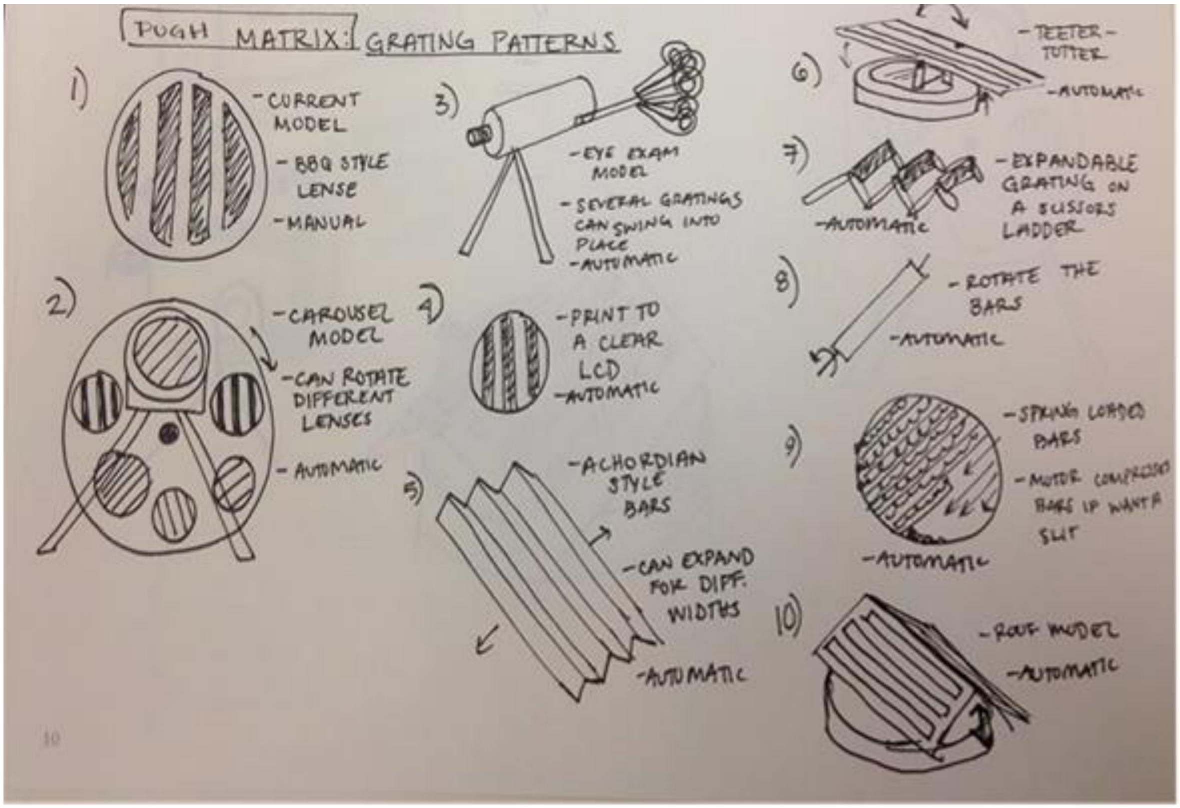


Figure 9. Ideation Sketches Drawn for Grating Patterns Ideas (StarT.E.K., 11/03/2014)

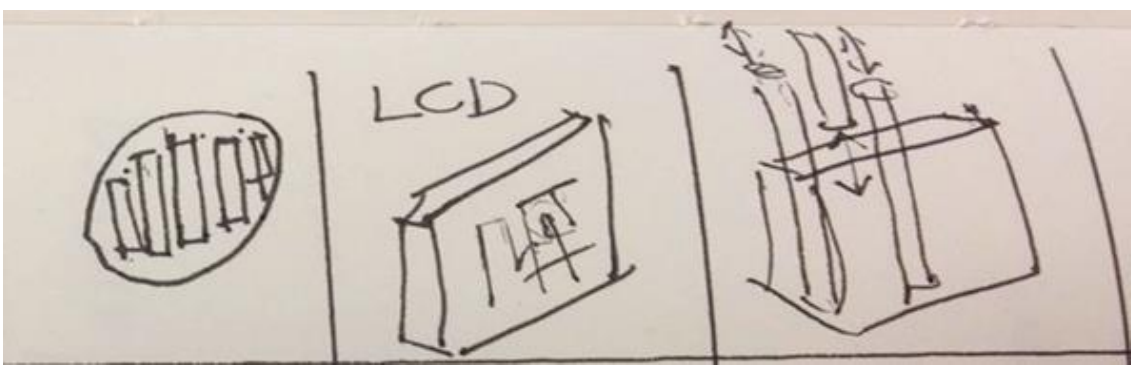


Figure 10. . Ideation Sketches Drawn for Grating Patterns Ideas (StarT.E.K., 11/03/2014)

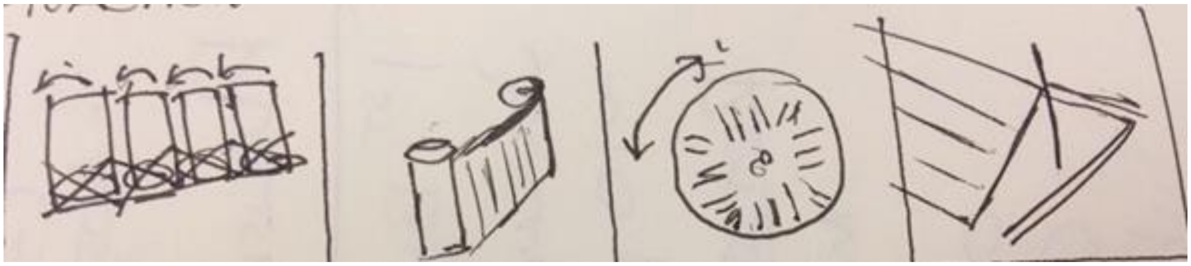


Figure 11. Ideation Sketches Drawn for Grating Patterns Ideas (StarT.E.K., 11/03/2014)

Figure 12. Ideation Sketches Drawn for Mounting System Ideas (StarT.E.K., 11/03/2014)

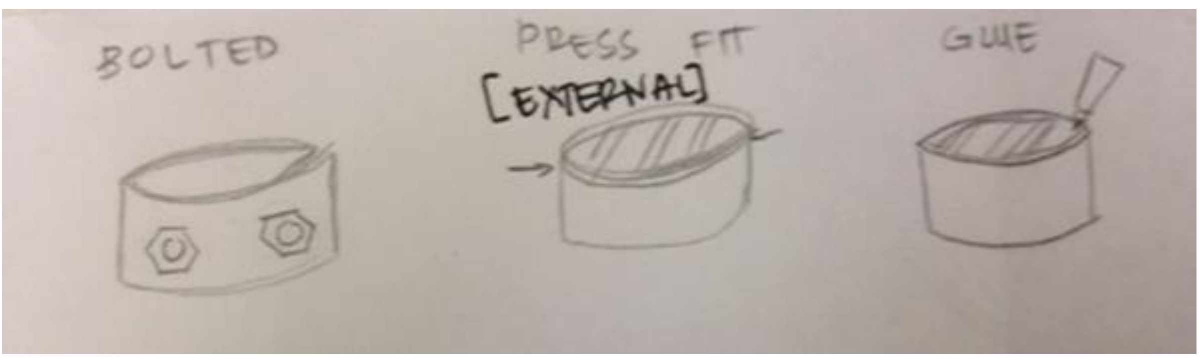


Figure 13. Ideation Sketches Drawn for Mounting System Ideas (StarT.E.K., 11/03/2014)

Evaluation of Rough Ideas

Before any idea can be ranked and evaluated, it must be capable of meeting all of the critical customer requirements and engineering specifications. One example of a simple system that eventually failed the critical system requirements was the simple mask with rotating bars. While a simple and lightweight system, this design is incapable of adjusting the spacing or "period" between bars. This means that the diffraction grating is not adjustable in such a way that would allow for the tracking of various binary stars.

As ideas developed, the concepts that showed promise in one or more of the desired areas were modeled or roughly prototyped. This allowed for the idea to become fully developed, and the details of its functions examined.

Design Matrices

Table 3. Abridged Comparative Matrix for Grating Criteria (Full Table Attached in Appendix B)

Grating					
	Size	Weight	Cost	Total	Weight Value
Size	0	0	-1	-7	1
Weight	0	0	1	-3	4
Cost	1	-1	0	-6	2
Adjustability	1	1	1	8	8
Durability	1	1	-1	-5	3
Simplicity	-1	1	0	-5	3
Safety	1	1	1	7	7
Speed	1	1	1	4	6
Transmissivity	1	1	1	11	10
Off the Shelf	1	-1	1	0	5
Precision	1	1	1	10	9
Over Hang	1	-1	0	-7	1
Ease of Removal	-1	-1	1	-7	1

One of the key methods used to evaluate and compare ideas is the engineering design matrix. This allows the design team to weight each of the attributes a design has, as well as rate how well a design fulfills it on a scale of 1-5. This gives each design an overall score that can be used to compare each design against the others, and the current technology. The tables and weighted categories are summarized below.

Weight Tables: To determine the weight or relative importance of each design attribute, each specification was charted, and compared against each of the other characteristics. If a specification is considered more important than the attribute it is being compared to it is given a +1. If less than, it is given a -1. Ties are scored with a 0. Once each attribute is scored, their overall rank is determined, and a weight values assigned. These weights are used to multiply the rating each design receives, factoring into the design’s overall score.

Diffraction Design Matrix

Table 4. Abridged Decision Matrix for Diffraction Grating Designs (Full Table Attached in Appendix B)

Grating		1		4		
	Size	x weight factor	Weight	x weight factor	Total	Rank
Standard Course Grating	5	5	5	20	218	9
Carrousel	1	1	2	8	216	10
Slide Show	2	2	1	4	194	13
Transparent LCD	5	5	3	12	233	3
Achordian	4	4	4	16	199	12
Teeter-Totter	2	2	3	12	230	4
Fixed Blade Scissor	4	4	3	12	241	1
Rotating Blade Scissor	4	4	3	12	224	7
~~Rotating Bars~~	5	5	4	~~16~~	~~221~~	~~8~~
Spring Loaded	5	5	3	12	230	4
Single Peak Roof	1	1	2	8	228	6
Multi-Peak Roof	3	3	2	8	234	2
Film Strip	4	4	4	16	229	5
Drop in Slats	2	2	2	8	202	11
Interchangable						

The evaluation of the Diffraction Grating itself focused on the following attributes:

Transmissivity: The primary function of the diffraction grating was also its highest weighted attribute. In order for the diffraction grating to function at all, it had to be able to block incoming light in such a way that would create a diffraction pattern. The grating also need to allow incoming light through without distortion. For the majority of designs, this criteria was simple enough - many designs had a through hole allowed all of the light through, and thus received a 5. However, some designs such as the film design or the LCD requires light to pass through a glass screen or film.

Precision: This category determines how small a tolerance is associated with the set diffraction pattern. Having a precise diffraction grating will allow for a greater accuracy in calculating the angular separation of the Binary stars.

Safety: A diffraction grating with no pinch points or mechanisms that could harm hands, or otherwise harm a user, is of the utmost importance.
Adjustability: Also ranking very high on the list of characteristics, is the range of adjustability of the diffraction grating. Just as diffraction is the key element in the grating itself, the

adjustability of the grating determines the range of stars that the diffraction grating can be used with, and is one of the key elements of the development of this project.

Speed: Anticipating that this project will eventually run automatically, speed is a concern. This will also simplify manual use.

Off the Shelf Parts: One of the goals of this project is that it be easily reproducible. In order to achieve this, the majority of components are desired to be off the shelf parts.

Weight: In order not to significantly slow or hinder the operation of the telescope, the weight of the diffraction grating system must be kept low.

Cost: In order for this project to appeal to as wide an audience as possible, a low cost is desired.

Simplicity: While simplicity is a concern in cost and manufacturability, it is worth sacrificing in exchange for a well-functioning system.

Size: While there is clearance around the telescope for large gratings or panels, keeping size to a minimum would allow it to be used more easily and in more confined conditions.

Mounting System Design Matrix

Hindering Motion of Telescope: Because the diffraction grating is designed to supplement existing telescopes, it cannot significantly hinder a telescope's operation. For the mounting system, this is especially important.

Permanent Modification of Telescope: This category was deemed important enough to receive its own weight factor. Any system must be designed to be mountable to a given telescope without damaging it or requiring modification.

Safety: Similar to the diffraction grating itself, the mounting system cannot be dangerous to any users.

Stability: The point where the diffraction grating system mounts to the telescope is the critical mechanism for maintaining stability in the system.

Cost: Like the rest of the Adjustable Diffraction Grating, the cost of the mounting system should be kept relatively low.
Weight: As with the diffraction grating itself, in order not to significantly slow or hinder the operation of the telescope, the weight of the diffraction grating system must be kept low.

Low Maintenance: While the overall Adjustable Diffraction System should be designed to be able to run automatically, and thus must be capable of running with little setup or maintenance, the mounting system must be even more solid and reliable.

Ease of Installation: Mounting the diffraction grating to the telescope must be a relatively quick and painless procedure, which does not permanently modify the telescope. Removal should be easy as well.

Size: While the mounting system must be able to fit on or around the telescope, it should not be large enough to interfere with the telescope operation or its range of motion.

Rotation Design Matrix

Accuracy: The most critical aspect of the rotation system is that it be able to accurately record the position angle that it is at. This is a requirement for making measurements of binary stars.

Precision: The rotation system that aligns the diffraction grating must also be precise. This allows for proper alignment and measurements when using the diffraction grating, as well as increasing the precision of the system's measurement as a whole.

Range of Motion: The rotation system must be able to rotate through the full 360 (or 180) degrees.

Speed: As with the diffraction grating, the rotation system must be able to complete its operations within a reasonable amount of time.

Cost: Like the rest of the Adjustable Diffraction Grating, the cost of the rotation system should be kept relatively low.

Strength: The rotation system must be capable of precisely rotating any chosen diffraction grating through the required movements.

Weight: As with the diffraction grating itself, in order not to significantly slow or hinder the operation of the telescope, the weight of the diffraction grating system must be kept low.

Durability: The rotation system should be reliable and capable of traversing the majority of its range of motion without fatigue.

Size: As the main mid portion of the system, the rotation system must not be overly bulky.

Discussion of Top ideas by Function

After each functional category was analyzed and ranked according to our customer requirements, we further discussed the top choices to make sure that we were satisfied with the results. The following designs ranked among the top five in their respective category, and were considered some of the best alternatives that need to be explained as to why they did not become our chosen concept.

Diffraction Grating

Figure 14. Film Strip Concept (Katieyunholmes, 11/11/2014)

Film Strip

The idea of using a film strip as a diffraction grating method consisted of a scroll with several sets of slits along its length. Each set of slits would produce a different diffraction grating depending on their width. The film would be held in cylinders attached on both sides of the telescope and scrolled along the front in order to switch to the appropriate grating needed.

The simplicity of this design makes it important to consider because its added weight and size would not affect the function of the telescope. In the case of having to remove the system and possibly mounting it to another telescope, this design would be easy to remove because it is composed of a small amount of parts that would not require an intricate form of set-up or disassembly. Unfortunately, this design would only provide a finite set of gratings, which although can be very precise, will limit the range of star separations that can be measured.

Another aspect considered was wear. The constant switch of gratings will wear the material used as film and may require continuous inspection to make sure that a new film is not needed. In order to replace the film, this would have to be an off-the-shelf item, but due to the high precision required from manufacturing each scroll, this would represent a costly design.

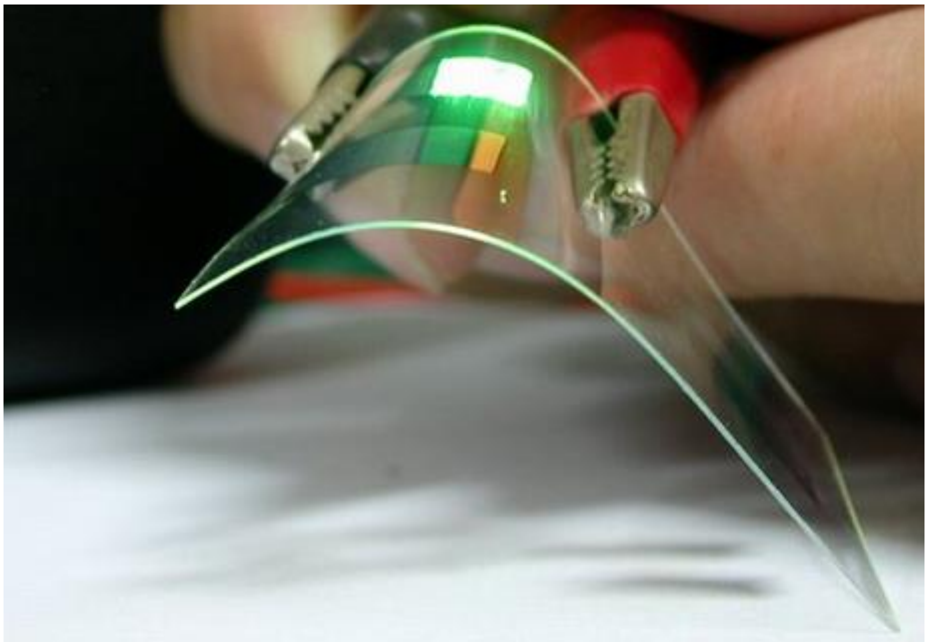


Figure 15. Transparent LCD (Wikipedia, 11/12/2014)

Transparent LCD

The use of a transparent LCD as a diffraction grating proved to be one of our favorites due to its versatility. The proposed idea was to use a computer to control and customize the type of grating to be printed. This grating would then be displayed on the LCD screen in order to observe binary stars and take data.

Having the advantage of being controlled by a computer and not human interaction makes this design more reliable because it is less likely to fail due to human error, which is more likely to occur than a hardware fail. The computer also allows for a faster response time which would increase the speed of the system by letting it adjust to any grating in a matter of seconds. The design could potentially produce a high number of gratings that would expand the amount of stars that can be analyzed. The advantage of its high speed would also let the observer obtain larger amounts of data per night, helping their research process easier and faster. The device does not have to take up a lot of space because its main component is just the screen, which is not made up of multiple mechanical components, thus making it easy for it to be interchanged between telescopes. The main problem with this design is the large cost of the crystal screen. Due to the minimum optical quality of transmissivity required from the diffraction grating

material, the crystal screen would have to be custom made. For it to meet our requirements for very specific dimensions and to minimal tolerances, manufacturing it would be extremely expensive. Additionally, many software components would be required to be installed in order to program its functions, which would add on to its cost and increase the virtual complexity of the system.

Figure 16. Rotating bar system (Dreshaj, 11/12/2014)

Rotating Bars

The implementation of rotating bars is similar to the use and function of venetian blinds. A number of bars overlap each other at a resting position and are able to change width as they are rotated, allowing different grating patterns to be produced. All bars would be rotated simultaneously and the total width of the grating could be reduced or expanded according to the astronomer's needs.

Although proven to be a very simple, lightweight, and low cost design, using rotating bars as a diffraction grating was not the best idea. Through basic modeling, it was found that if the bars were not to overlap each other, they would require a small clearance in between them in order to be able to rotate. Rotating all bars simultaneously may create different grating patterns, but it does not change the period, the distance between one center of the bar to the next. The period is a crucial part of our design because equally distanced slots produce the best results, and not being able to vary the period makes the design be less competitive.

Mounting System

Figure 17. Band clamp (2.50, 11/13/2014)

Band Clamp

One of the simplest and most effective means of strapping two objects together - especially round ones - is the band clamp. This ring can be tightened down in order to securely grip the telescope, and can be easily adjusted to a moderate range of sizes. This ideas was chosen over the Chuck or Spring Loaded Feet designs after the requirement for mounting to multiple telescopes was removed. The biggest benefits of this design are the extreme simplicity, the ease with which band clamps could be swapped out in order to fit other telescopes, and the fact that you can maintain a secure attachment to the telescope, without permanent modification.

Spring Loaded Feet

This design involves the use of a 4-bar mechanism which is spring loaded. These feet would swing down and squeeze the telescope from three sides, centering and securing the diffraction grating system. The design of the mechanism also allows for mounting to a wide range of telescopes, by swinging out or collapsing the spring loaded feet.

This design scored highly on our design matrix; however, the wide range of allowable telescope sizes that is the main strength of this design is not worth the complexity involved.

3-Jaw Chuck

A very common design in Mechanical Engineering, a “wide jawed chuck” is an easy means to mount or grip a round object such as a tube or a telescope. While this design is well known and

well developed, the complexity and weight make it hard to justify when it comes to simple designs like the band clamp.

Figure 18. Typical 3-Jaw Chuck (Wikipedia 11/12/2014)

Rotation System

Servo Motor

The simplest method of rotating a diffraction grating would be to mount a small servo motor to the center obstruction of the telescope. This servo motor would then rotate the mask or diffraction grating directly around the telescope's axis.

This ideas was ultimately deemed impossible due to the difficulty of mounting a servo motor to the plastic center obstruction of the telescope, without permanently modifying or damaging the telescope's center obstruction cap.

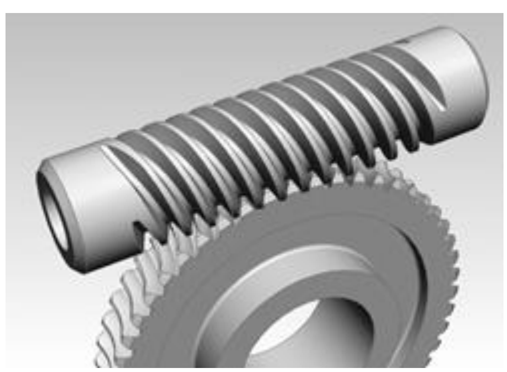


Figure 19. Worm Gear (Wikipedia, 11/11/2014)

Gear System

A crown gear or a spur gear could be used to rotate the system. While this is a familiar and seemingly simple system, the implementation requires machining gears or a tooth set large enough to fit around the telescope and mounting system. This approach, while well developed, would be expensive to implement, due to the cost of machining large gears/teeth. It would however be precise.

Cable/Pulley System

An extremely simple system for rotating a system or wheel is the pulley system. In this setup, a single rotary motor could be used to pull on cables that would rotate the diffraction grating system.

While this system is extremely simple and efficient, pulley systems do tend to slip. This would significantly hinder the precision of the system as a whole.

Figure 20. Chain drive (StarT.E.K., 11/12/2014)

Chain Drive

The concept design that was finally selected, as it combines the extremely simple Cable /Pulley system, with the accuracy and power of a gear tooth system.

Supporting Preliminary Analysis

Preliminary testing was performed in order to ensure that we can get a grating that will cover the entire surface of the telescope lens, and be able to expand to 5 times its original size. We decided that when the scissors are fully extend, we will have 4 bars across the lens and 3 spaces

(for a total of 7 equispaced rectangular grids). Since the telescope diameter is 11in, we divided 11 by 7 to get the needed width of the gratings; 1.57 in. We divided this number by cosine of the minimum angle that the scissors can reach (10 degrees). This gave us a value of 1.6 in, but we chose to use 1.5 in our final design because it is a more common width.

Proof of Concept Testing

Table 5. Carriage Proof of Concept Testing Results Part I

Testing #	Parts Being Tested	Testing Conditions	Testing Procedure	Testing Results
1.0	• Chain: **Plastic** • Carriage • Telescope	• Telescope: Horizontal	• Marked initial position of belt • Moved carriage one way then the other • Held one side (loose ends together) • Moved sprocket only (rotated)	• Worked perfectly • Easy to move
2.0	• Chain: **Plastic** • Carriage • Telescope	• Chain: No tension • Telescope: Vertical	• Marked initial position of belt • Moved carriage one way then the other • Held one side (loose ends together) • Moved sprocket only (rotated)	• Hard(er) to move around • Belt moved out of place
3.0	• Chain: **Plastic** • Carriage • Telescope	• Chain: No tension • Telescope: Vertical • Carriage: Put to one side	• Marked initial position of belt • Moved carriage one way then the other • Held one side (loose ends together) • Moved sprocket only (rotated)	• Belt slipped a little (got stuck on a piece) • Displacement after turning one way: 2.1in • Displacement after turning the other way: 2.8 in (0.7in in addition to 2.8 in)
3.1	• Chain: **Plastic** • Carriage • Telescope	• Chain: Medium tension • Telescope: Vertical	• Marked initial position of belt • Moved carriage one way then the other	• Displacement of belt: down 0.1inch • Hard to move belt

			• Held one side (loose ends together) • Moved sprocket only (rotated)	

Table 6. Carriage Proof of Concept Testing Results Part II

Testing #	Parts Being Tested	Testing Conditions	Testing Procedure	Testing Results
4.0	• Chain: **Plastic** • Carriage • Telescope	• Chain: Low tension • Telescope: Vertical • Rail: High tension • Resting on rail	• Marked initial position of belt • Moved carriage one way then the other • Held one side (loose ends together) • Moved sprocket only (rotated)	• Belt did not move
4.1	• Chain: **Plastic** • Carriage • Telescope • Rail	• Chain: High tension • Telescope: Vertical • Rail: High tension • Resting on rail	• Marked initial position of belt • Moved carriage one way then the other • Held one side (loose ends together) • Moved sprocket only (rotated)	• Belt did not move • Hard to move belt, especially at the beginning
5.0	• Chain: **Metal** • Carriage • Telescope	• Chain: High tension • Telescope: Vertical • Changed wheels on carriage to rubber tires	• Marked initial position of belt • Moved carriage one way then the other • Held one side (loose ends together) • Moved sprocket only (rotated)	• Displacement after turning one way: 1in • Additional displacement after turning the other way: 0.75in • Much easier to move than plastic belt at high tension • The oscillation of the wheels helped the carriage move more easily on high tension
6.0	• Chain: **Metal** • Carriage • Telescope • Rail	• Chain: High tension • Telescope: Vertical • Rail: High tension • Resting on rail	• Marked initial position of belt • Moved carriage one way then the other	• Belt did not move • Easy to move carriage

		• Changed wheels on carriage to rubber tires	• Held one side (loose ends together) • Moved sprocket only (rotated)	

Table 7. Carriage Proof of Concept Testing Results Part III

Testing #	Parts Being Tested	Testing Conditions	Testing Procedure	Testing Results
7.0	• Chain: **Metal** • Carriage • Telescope • Attached Motor	• Chain: High tension • Telescope: Vertical • 12V DC motor was attached to the carriage • Changed wheels on carriage to rubber tires	• Marked initial position of belt • Moved carriage one way then the other • Held one side (loose ends together) • Motor attached to sprocket (rotated)	• Displacement after both passes: 0.75in • Easy to move carriage • Motor worked great!
8.0	• Chain: **Metal** • Carriage • Telescope • Rail • Attached Motor	• Chain: High tension • Telescope: Vertical • Rail: High tension • Resting on rail • 12V DC motor was attached to the carriage • Changed wheels on carriage to rubber tires	• Marked initial position of belt • Moved carriage one way then the other • Held one side (loose ends together) • Motor attached to sprocket (rotated)	• The wheels rolled over the rail, but if we had higher rail, it would keep the belt in the correct spot • Easy to move carriage • Motor worked great
9.0	• Chain: **Metal** • Carriage • Telescope • Force Meter	• Chain: High tension • Telescope: Vertical • Changed wheels on carriage to rubber tires • Force meter attached to sprocket	• Motor was unattached • Measured the tension of the belt with the force meter • Force meter was attached to a moment arm which was attached to the sprocket • Force meter was pulled at a constant rate and the value was recorded when	• The tension of the belt was measured to 13lb • We did 20 passes in each direction • Ave Torque needed for 13 lb Tension = 13 oz-in

			it was perpendicular to the carriage	

Our proposed chain and carriage mechanism required proof of concept testing. Because the idea does not seem to be applied elsewhere, there are no current ways to prove its functionality theoretically through preliminary analysis. To verify that we could move on with this idea, we did a series of tests with two different types of driving systems: a metal and a plastic/rubber chain. The types of tests and results are shown in Tables 5-7 above. We built a carriage out of Lego parts and wheels and placed the appropriate sprocket gears to it as originally planned. A 12" concrete form tube was used to model the telescope and a rubber tarp strap was placed around it to act as guiding rails for the carriage. We used a power supply to power a 12V DC motor that was connected to the sprocket gears in the carriage. Once running, the chain and sprockets would drive the carriage around the telescope and confirm that the concept would work (Figure 21).

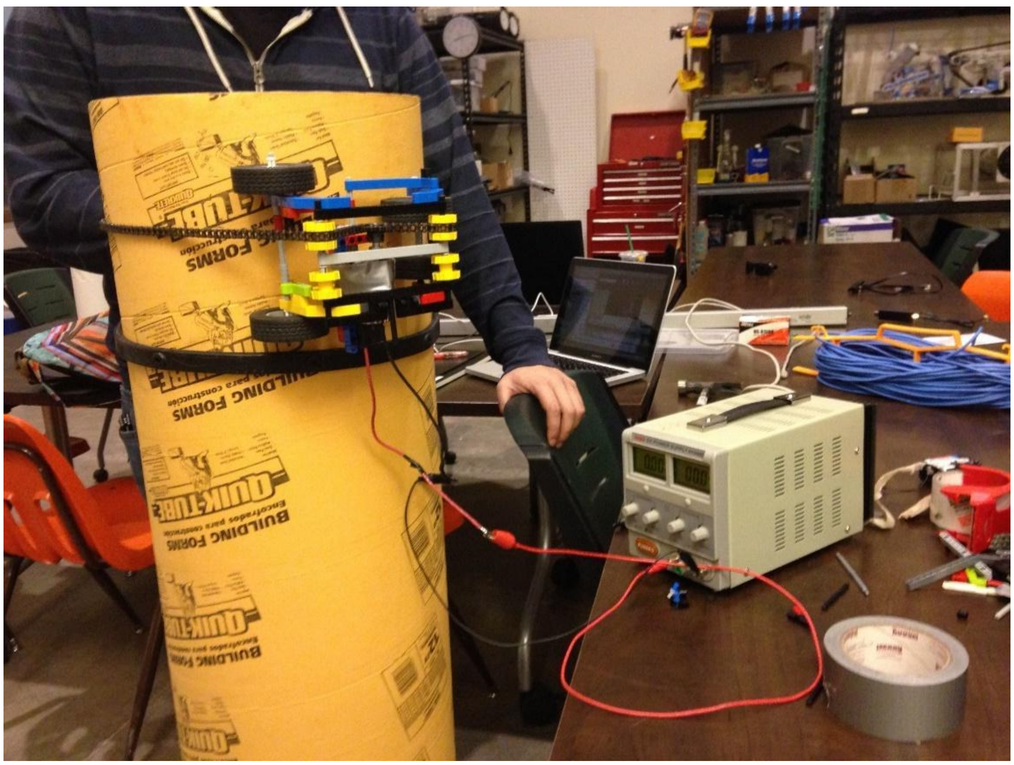


Figure 21. . Testing Set Up Using Metal Chain and Sprocket (StarT.E.K., 01/30/2015)

Even though the concept was confirmed the first time it was tested, we confirmed our tests using both types of chains (plastic/rubber and metal) and varying other parameters such as the tension of the chain, the tension of the tarp strap, the types of tires used and the position of the telescope (Figure 21 and Figure 22). We found that in order to make sure the carriage would not be affected by the added weight of the grating, the chain had to be kept in high tension. The average torque needed to keep the chain under this amount of tension was then found by using a force meter and doing several passes in each direction (Figure 23). This resulted in an average torque of 13 oz.-in needed for the required 13 lbs. of tension.

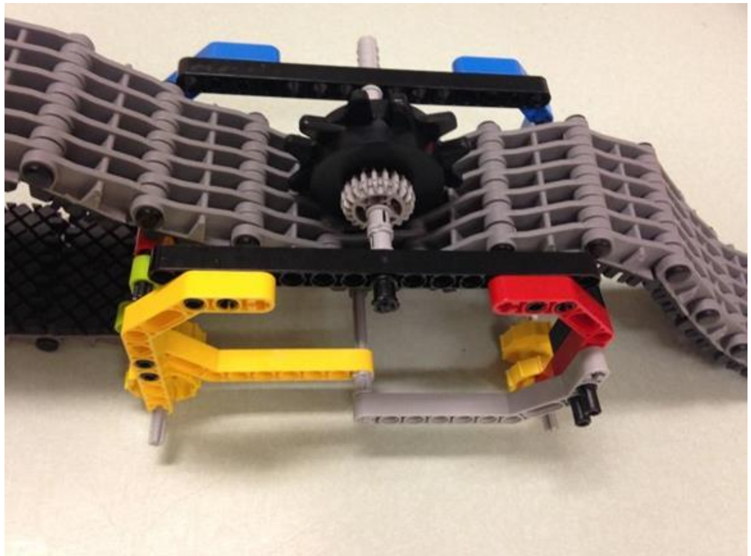


Figure 22. Carriage Testing with Plastic Chain and Sprocket Gears (StarT.E.K., 01/30/2015)

Figure 23. Maximum Torque Test on Chain/Carriage Mechanism (StarT.E.K., 01/30/2015)

Chapter 4: Description of the Final Design

Final Design Model

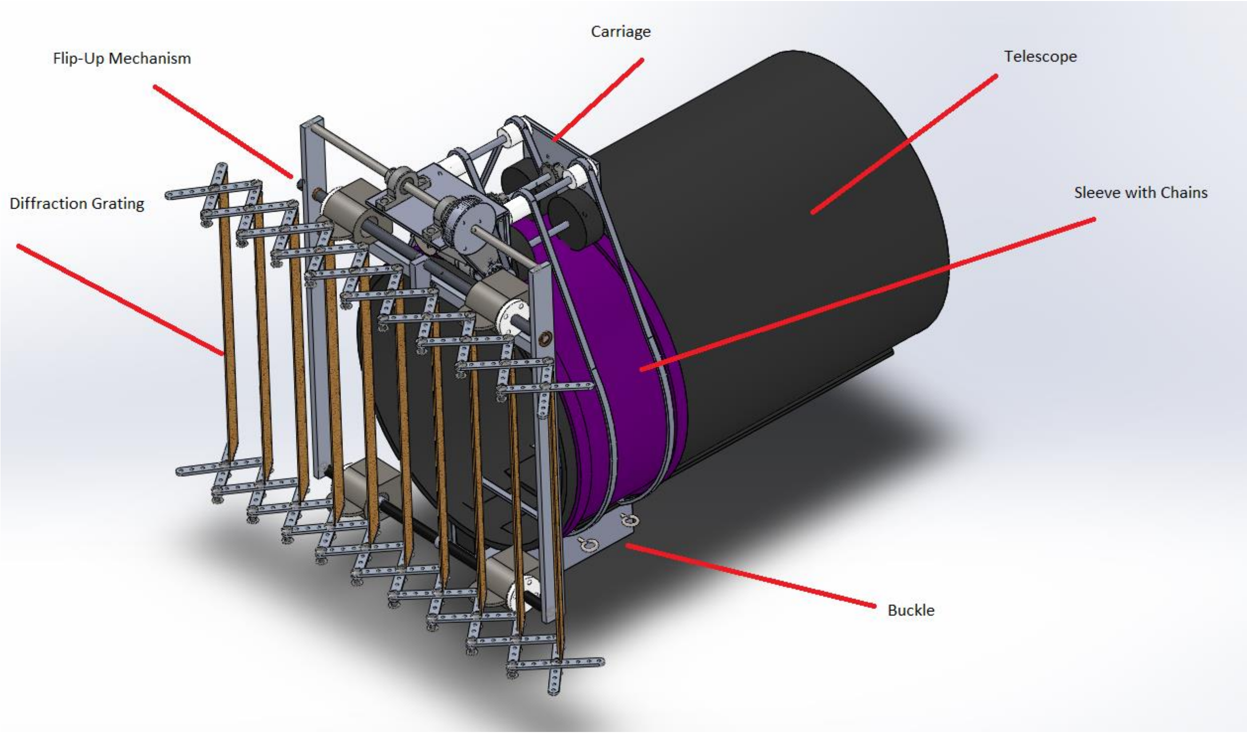


Figure 24. Overall Assembly (StarT.E.K., 02/01/2015)

Detailed Design Description

Each component was designed based on calculations that are referenced in the explanations below. See Appendix E for the in depth analysis. All of our dimensions were determined using a factor of safety of 5 to account for interference by the surroundings, variations due to abnormal orientation of the system and losses due to friction that were neglected in some of our calculations.

The main functionality of this design comes from the *Diffraction Grating subsystem.* The grating itself consists of lightweight slats attached at either end to a scissor mechanism. This is the device that allows variable diffraction patterns to be formed.

The *Carriage* allows the entire Automatic Diffraction Grating system to be driven around the outside of the telescope via the *Chain* system. The Carriage also houses the electronics and actuators responsible for controlling the position of the Diffraction Grating.

A *Buckle* and *Sleeve* have also been added to the system, primarily to support and enhance the *Chains* that drive the carriage.

Diffraction Grating

The scissor mechanism is a simple and compact method for adjusting the diffraction grating with the following features:

- Simple and wide range of adjustment.
- Maintains the ratio between the bars and slots.
- Can be actuated with a single motor.

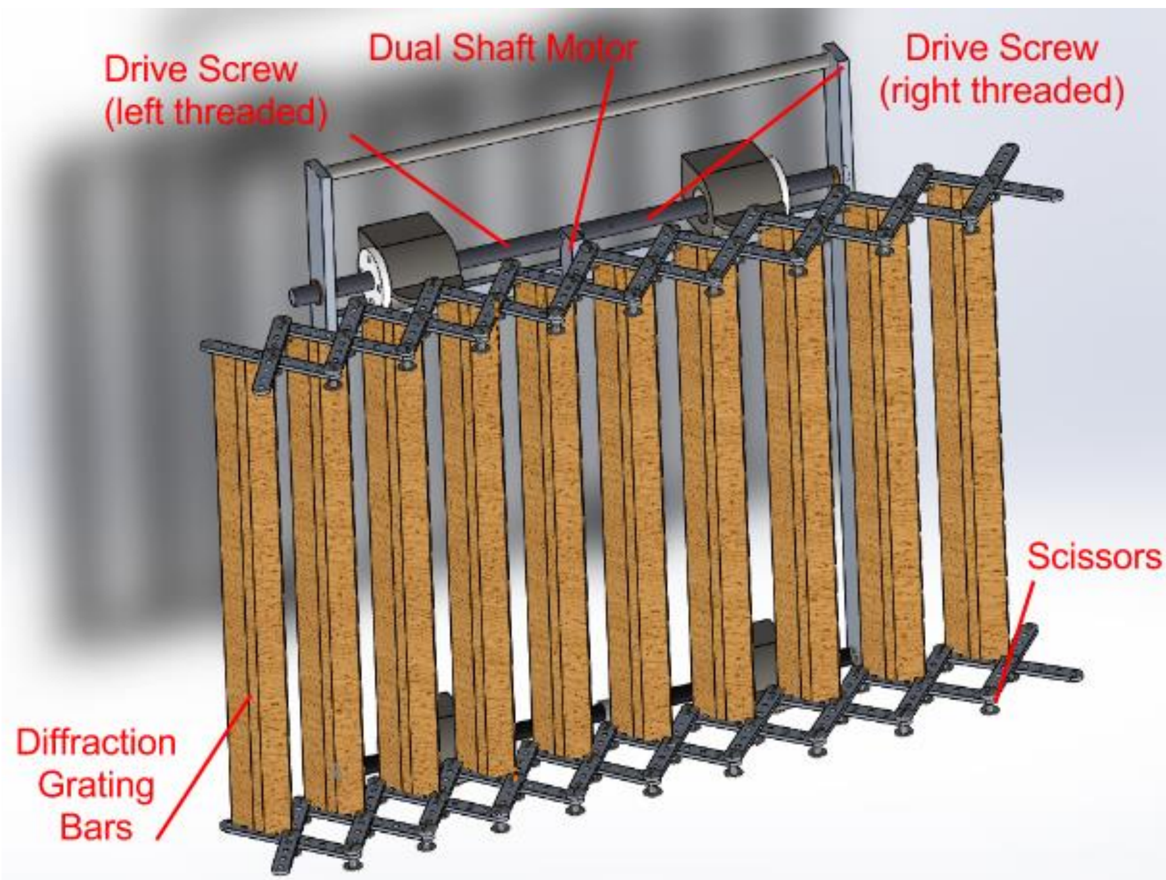


Figure 25. Grating and Scissors (StarT.E.K., 02/01/2015)

This design was the highest ranked in our design matrix analysis and allows the grating to reach five times its initial width when fully extended, which means the diffraction pattern would have a ratio of 1:5 when fully extended. We will be using flat aluminum beams that are 3

inches long and 1/16 inches thick as the diffraction grating bars. We designed the scissors to have rounded edges so they are more user friendly and reduce the possibility of injury. We stacked two plates together in order to make the system thicker and more stable. There will be 10 aluminum double plated scissor beams on each side of the grating and they will be used to adjust the spacing between gratings. They will be actuated by a dual shaft direct current (DC) motor attached to two opposite threaded drive screws. The geometry of the scissors were determined from the calculating the minimum deflection and reverse engineering the dimensions. The scissors themselves will be attached to nuts that move in opposite directions when the drive screws are spinning. The minimum drive screw was determined based on the maximum allowable torsion on the screw. An outer frame was constructed to support the scissor and grating mechanism because it provided more stability and allowed for the grating to be thinner and lighter. We analyzed the maximum allowable deflection of the grating and used the results to determine the geometry of the frame. These calculations can be seen in Appendix E. The grating itself is made of 1.5 in light-weight plastic rulers and as the scissors expand, the gratings tilt which changes the width of the effective grating shadow. These various shadows are what create the pattern that we then use to analyze the binary star system.

Carriage and Chains

A carriage is used to rotate the diffraction grating around the outside of the telescope. This is an important feature because the grating has to be perpendicular to the orientation of the binary stars in order to obtain an accurate diffraction pattern. The carriage is driven using a chain belt and sprocket gear mechanism that is simultaneously used to mount the entire device onto the telescope itself. The chain belt "hugs" the outside of the telescope and remains stationary when appropriately tensioned.

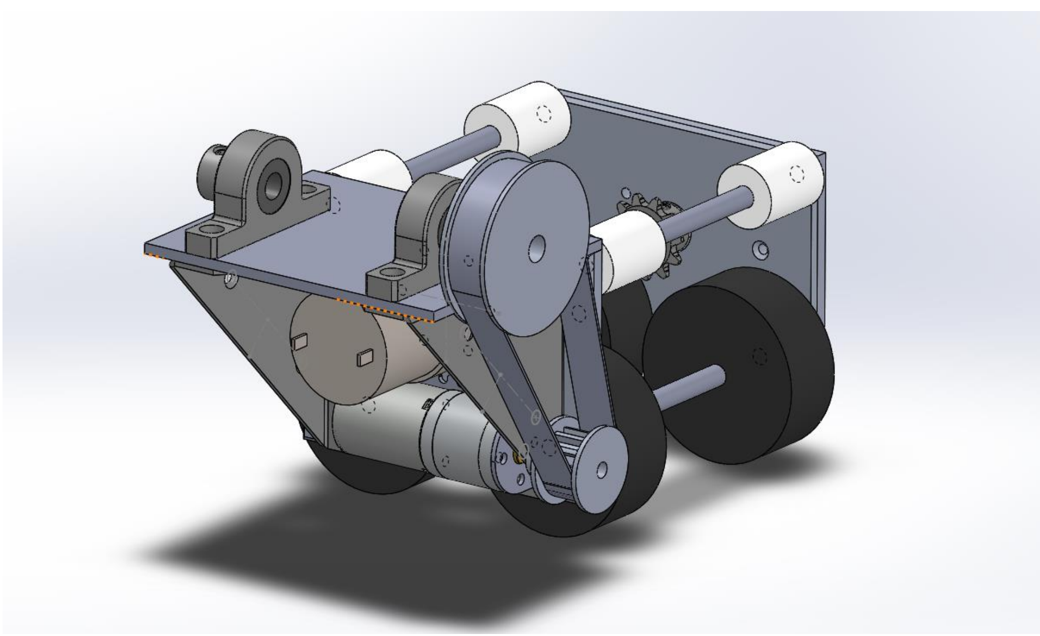


Figure 26. Carriage View 1 (StarT.E.K., 02/01/2015)

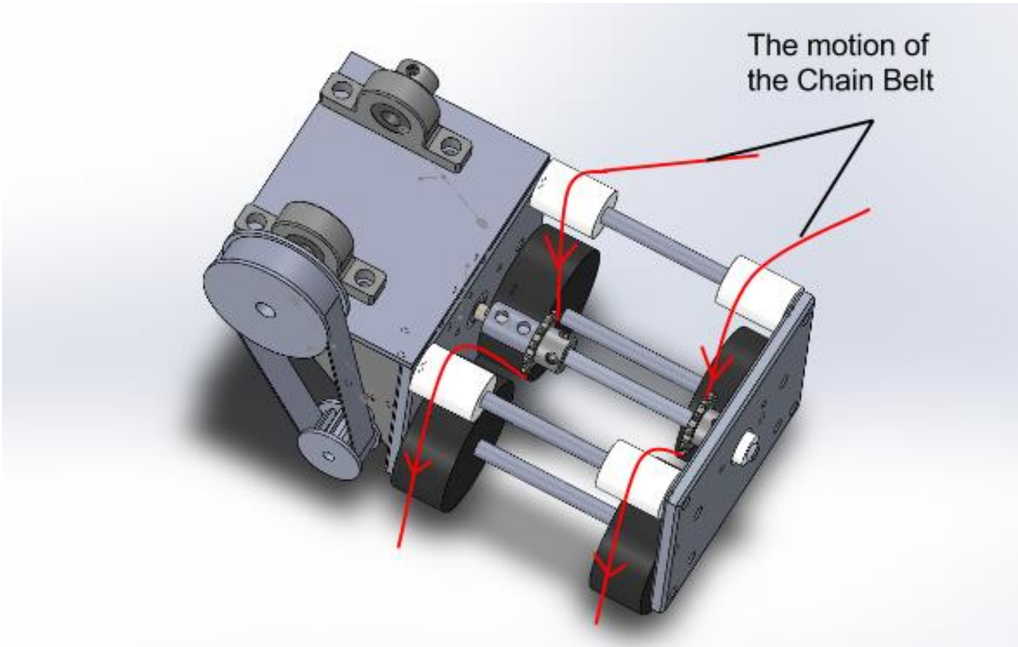


Figure 27. Carriage View 2 (StarT.E.K., 02/01/2015)

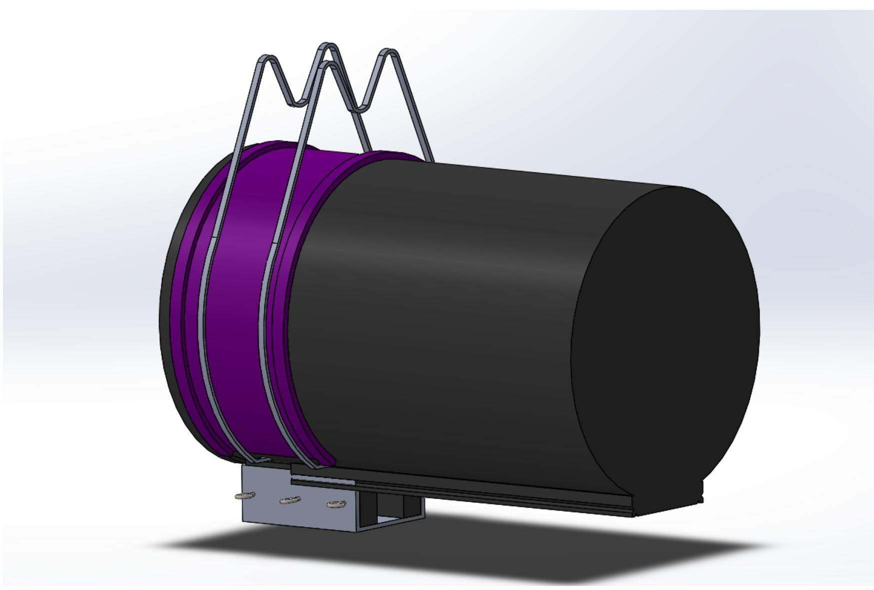


Figure 28.Belt and Guide Rails (StarT.E.K., 02/01/2015)

A simple chain belt design is used to combine the mounting and rotation functionality. A tight belt is used to secure the carriage to the telescope, and will be fed through a geared motor integrated into the carriage. This allows the carriage to "crawl" along the belt on the outside of the telescope. This design combines the accuracy of a gear system with the incredible simplicity and adjustability of the cable system. The belt will be tightened to a tension of 13 lb. in order to keep the carriage fastened to the side of the telescope. The belt attaches to hooks that are fastened to the side of a buckle on the belly of the telescope which can be seen in Figure 28. This buckle is designed to fit over the axis rail of the Celestron C-11 telescope. We designed a double chain motor drive in order to counteract the moment applied by the attached grating system. The chain belt will initially go over spacer in order to reach the desired tension and then underneath the two sprockets to control the movement of the carriage. Guide rails will be put in place ensure that the chain does not slip off of the spacers. A single motor will be attached to a drive shaft to control both sprockets simultaneously. To our knowledge, this type of design has never been seen before. Typically when a chain belt is used to move a system, the belt itself is rotating, such as chains on a bicycle. However, in our design the belt is the stationary component and the carriage rotates. Because this system is unique we did not know if it would even work and there are so many factors and forces that are acting on it, it would be very difficult to examine analytically. So we developed a prototype of the carriage system to test our invention. There is more detail about the test in Chapter 3. The tests proved that our system will work. Underneath the belt is a neoprene sleeve that wraps around the end of the telescope and acts as a road for the carriage. The sleeve has inserts on each side that act as a guide rail for the carriage as it travels across the circumference of the telescope. We tested this concept, and the guide rails kept the carriage from straying off its course.

Flip Up Mechanism

A timing belt is used to rotate the diffraction grating off the front of the lens, flipping it up and out of the telescope's line of sight. The larger timing pulley has a 2:1 ratio and is attached to one end of the support frame with the grating on it. A 300 oz.-in DC motor is attached to the smaller pulley and rotates the entire grating mechanism 90 degrees so that it is sticking straight up, perpendicular to the face of the telescope. This feature allows the user to continue to use the telescope remotely without the visual obstruction of the grating. There is a boolean control in the user interface that allows the user to decide if they want the grating system on or off. When the telescope is being stored, the user must return the grating to its post at the face of the telescope and the case can slide over the entire mechanism.

Analysis Results of Design

After our preliminary design was approved by our sponsors, we began conducting analysis to prove that our design is plausible. We used our calculations to determine the geometry of our

components and to verify that our design will not fail. Below is a description of the different calculations we performed and the detailed analysis can be seen in Appendix E.

Grating Stiffness Analysis

Initially we planned on using the grating itself as a support frame to suspend the scissors at the far end. So we analyzed the grating as a single cantilever beam with a distributed load along the beam and a point load at the end of the beam and multiplied the results by the number of grating (10). The distributed load is the weight of the grating itself and the point load is the weight of the scissors and the guide rails that they slide along. We solved for the thickness of the grating using the deflection equations for a cantilever beam:

$$\delta = \frac{WL^4}{8EI} + \frac{PL^3}{3EI}$$

Where δ is the deflection, W is the distributed load and P is the point load. Rearranging the equation and using an assumed length and width of the grating, we calculated the minimum thickness of the beam to keep the deflection under 0.016 in (or 1 percent tolerance of the grating). We performed the calculations for having the grating, scissors, and guide rails made of aluminum, for all three components made of ABS plastic, and for grating made of plastic, but with scissors and guide rails made of aluminum.

The resulting minimum thickness were 0.16 in, 0.636 in, and 0.68 in, respectively.

Support Frame Analysis

After initial analysis the results of the grating stiffness analysis, we chose to go with aluminum gratings of 0.16 in thickness and aluminum scissor mechanisms. But when we began doing the analysis for the motor of the flip up mechanism, the overall weight of the grating system was too large to move. So we decided to create a square support frame with a bar 5 inches from the hinge end to hold the scissor-grating mechanism (see Figure 29 below). This way we only need two sturdy supports on the side of the frame and the grating can be very thin and light-weight.

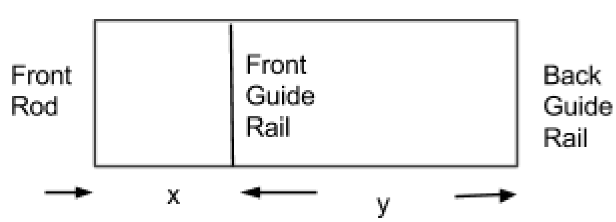


Figure 29. Support Frame (StarT.E.K., 02/01/2015)

We initially used the values of x = 5 in., and y = 12 in. We assumed the geometry of the front rod, and both guide rails then solved for the geometry of the two side supports. Using the deflection equations above, we solved for the thickness of the support with respect to the base width and developed the following equation:

$$t = \sqrt[3]{\frac{0.15486}{b}}$$

Where t is the thickness of the side supports, and b is the base width. We plugged this equation into excel and decided that 0.5 in x 0.5 in would work best for our application. After a few iterations of our design we have changed these dimensions due to assembly constraints which you can read more about in the geometry selection section.

Flip Up Mechanism Analysis

The flip up mechanism will allow the user to remove the grating from its view at any given time from the comfort of their warm room. In order to actuate the flip up mechanism, we needed to know the amount of torque needed to be provided by the motor in order to rotate the grating from a starting angle of 0° with respect to the front face of the telescope, to any angle up to 270° counterclockwise. Simple dynamics analysis was carried out to find the torque. By drawing the appropriate Free-Body-Diagram and Kinetic Diagram and summing the moments about the hinge that would be rotating, we were able to find a general equation for the moment about the hinge in terms of the variable ϴ. In order to make the analysis easier, the parallel-axis theorem was used to analyze the mechanism about the hinge instead of about its center of gravity.

Estimated dimensions were determined for the scissor bars and the grating bars in order to find their corresponding volume and mass. Mass calculations were estimated for the possible use of aluminum or ABS as our principal material due to their advantageous resistance to corrosion. It was found that the use of aluminum for the grating bars would only require approximately 0.16in of thickness, while for ABS a thickness of 0.64in was required. Although the density of ABS is smaller than the density of aluminum, the difference in thickness required from each material showed that ABS would add a lot more weight to the system, thus requiring a higher torque from the motor actuating the flip up mechanism.

Power Screw Analysis

The power screw analysis involved some preliminary research to see what materials were available and what were the smallest diameters provided by manufacturers. The shaft was then analyzed using the Goodman fatigue failure criteria. This method was used under the assumption that the power screw could be treated as a smooth shaft with no change in diameter. However, when calculating the stress concentration factors, the threads did have to be taken into account. This was easily found in Shigley's Table 8-16. Because the fatigue failure criteria is just like any design process in which iteration is required as means to find the best

possible alternative, an initial guess had to be made about the diameter of the shaft (the screw), and once the actual diameter was obtained, using excel, the calculations went through an iterative process until the correct minimum diameter was found.
The diameter of the screw helped determine its size, but it also needed to be driven by a motor and its requirements for the motor had to be analyzed. By calculating the amount of torque needed to raise and lower the load acting on a power screw, one could see where a higher torque is needed, and we can base our decisions for buying a motor based on our limiting factor, which in this case would be the higher torque. In order to help with other calculations needed to determine the dimensions and stiffness needed for the frame box that would be supporting the grating, the forces needed to move the load up and down, or side to side, were also found.

Scissor Mechanism Analysis

One of the most complex mathematical analyses performed was the calculation of the necessary size of the individual linkages of the scissor mechanism.

First, the worst case scenario for the scissor mechanisms was found to be when they are oriented to expand or collapse in the direction of the vertical plane, and are in their most collapsed state. This position results in the maximum amount of bending, assuming that each linkage can be treated as a 2D beam. Taking the driven linkages as our primary beams, the weight of the grating bars and other linkages, are applied as forces to the primary beam, and that beam is used to calculate the maximum deflection in a linkage (Appendix E). Using this deflection as our worst case scenario, we can then calculate the Area Moment of Inertia required to limit the deflection of any given diffraction grating bar to less than the allowable 0.015”. This in turn allowed us to specify a linkage cross section, which was chosen as 0.25 x 0.25 in.

After the Area Moment of Inertia required to prevent excessive bending was found, the scissor mechanism was analyzed for torsion and twisting. Initially, the secondary scissor mechanism was supported entirely by the diffraction grating bars, which acted as cantilevered beams between the primary and secondary scissors. This meant that in certain positions the individual linkages of the scissor mechanism would be subject to a significant load. This load was found to be 6.875 lb.-in. Rather than attempt to design the scissor mechanism to be able to withstand this load, these findings contributed to the decision to reinforce the frame supporting the scissor mechanisms.

Sleeve Tension Analysis

The sleeve is in direct contact with the telescope and its purpose is to keep the belt straight. One way it does this is by applying a frictional force against the motion of the belt to keep the entire system from slipping. The most extreme case that the sleeve will slip is when the

telescope is completely vertical and the forces acting on the carriage are the weight of the entire system. Doing a simple free body diagram, we determined the following equation:

$$T_{required} = \frac{F_d}{2\mu}$$

Where T is the required tension of the sleeve, F_d is the disturbance force, which is the weight of system in this case, and μ is the coefficient of friction between rubber and steel. This equation told us that the tension needed to be 3.2 lbs. in order for the sleeve to not slip. We later chose to use neoprene instead of rubber because it is easier to work with and has better friction properties. Neoprene's coefficient of friction is twice that of rubber, so the required tension is half as large, and making it the better choice.

Carriage Dimension and Belt Tension Optimization

When selecting the size of the carriage, a number of factors were taken into account. The most important of these was the tension required to keep the carriage secured to the telescope, given the moments applied to it, as well as the size of its base. This tension was found to be:

$$Tension = \frac{M}{(Dcos(\Theta_1)}$$

Where D is the depth of the carriage (length along the telescope). Θ_1 is calculated from the overall geometry of the telescope and the carriage (Appendix E). Optimizing this equation to minimize the required tension tells us that the optimal size for the carriage is 4" W x 3" H x 6 " D. Using these dimensions, the required tension in the belt was found to be 6.067 lbf. These dimensions were followed as closely as possible, and a second chain was added for additional support.

Cost Analysis

The following tables show a list of parts for different components of the diffraction grating system and their corresponding cost analysis.

Table 8. Cost Analysis (1 of 8).

Vendor	Part Number	Item	Cost Per Item	Quantity	Total
Home Depot		Adjustable Rubber Strap	$2.98	1	$2.98
		Quick Link 1/8", Zinc, 3Pk	$3.28	1	$3.28
		Kleenex Box	$1.88	1	$1.88
		12"x48" Tube for Concrete	$11.42	1	$11.42
		Ratcheting Tie Downs	$13.87	1	$13.87
McMaster-Carr	91772A110	18-8 Stainless Steel Pan Head Phillips Machine Screw, 4-40 Thread, 1/2" Length, Packs of 100	$4.45	1	$4.45
	8975K595	Multipurpose 6061 Aluminum, Rectangular Bar, 1/4" X 7/8", 3' Long	$6.34	1	$6.34
	9440T15	Graphite SAE 841 Bronze Flange Bearing, for 5/16" Shaft Diameter, 7/16" OD, 3/8" Length	$1.20	2	$2.40
	1688K8	Oil-Lubricated SAE 841 Bronze Sleeve Bearing, for 3/8" Shaft Diameter, 1/2" OD, 1/4" Length	$0.73	4	$2.92
	8554K27	Self-Lubricating MDS-Filled Nylon Rod, 3/8" Diameter, Black	$0.95	5	$4.75
	89535K86	Multipurpose 304/304L Stainless Steel Rod, 5/16" Diameter, 1' Long	$3.09	1	$3.09
	8975K596	Multipurpose 6061 Aluminum, Rectangular Bar, 1/4" X 7/8", 3' Long	$3.13	1	$3.13
	9946K12	Set Screw Shaft Collar, for 5/16" Diameter, Aluminum	$2.52	1	$2.52
	51514T512	Trapezoidal Tooth Silicone Timing Belt, .200" Pitch, Trade Size 100XL, 10" Outer Circle, 1/2" W	$21.58	1	$21.58
	57105K13	Acetal Pulley for XL-Series Timing-Belt, for 1/4" & 3/8" Belt Width, 1.00" OD, 12 Teeth	$7.48	1	$7.48
	57105K24	Acetal Pulley for XL-Series Timing-Belt, for 1/4" & 3/8" Belt Width, 2.00" OD, 28 Teeth	$8.75	1	$8.75
	5395T113	Set Screw Rigid Shaft Coupling, without Keyway for 6MM Diameter Shaft, Type 303 Stainless Steel	$8.95	1	$8.95
	1265K51	Metric Miniature Type 316 Stainless Steel Drive Shaft, 6 mm OD, 200 mm Length	$19.38	1	$19.38
	2685T11	Metric PTFE Sleeve Bearing, for 6MM Shaft Diameter, 12MM OD, 10MM Length	$3.55	2	$7.10

Table 9. Cost Analysis (2 of 8)

Vendor	Part Number	Item	Cost Per Item	Quantity	Total
McMaster-Carr	9960T72	Skate Wheel, Rubber on Steel, 2-1/16" Diameter X 3/4" W, 100 lb Cap	$4.04	4	$16.16
	91125A320	18-8 Stainless Steel Female Threaded Round Standoff, 1/4" OD, 4" Length, 4-40 Screw Size	$4.64	4	$18.56
	92825A147	Plastic Unthreaded Spacer, 3/4" OD, 1" Length, .260" ID, Packs of 20	$10.57	1	$10.57
	1088A32	Inside Corner-Reinforcing Bracket, 3" Length of Sides	$2.59	2	$5.18
	5912K2	Self-Lubricating Aluminum-Mounted Bronze Bearing, Base Mounted, for 5/16" Shaft Diameter, 2 1/4" L	$10.33	2	$20.66
	2737T3	Finished-Bore Sprocket for ANSI Roller Chain, for #25 Chain, 1/4" Pitch, 11 Teeth, 1/4" Bore	$9.09	1	$9.09
	93121A320	Low-Profile Binding Post, Aluminum, for 3/16" to 1/4" Thick Material, Packs of 50	$10.44	1	$10.44
	3190T12	Vibration & Noise-Damping Strut-Mount Clamp, for 13/16" Outside Diameter, 1/2" Pipe	$3.54	4	$14.16
	9433K47	Precision Stainless Steel Extension Spring, 2.50" Length, .500" OD, .063" Wire Diameter, Packs of 3	$6.87	2	$13.74
	3482T11	Type 304 Stainless Steel Light Duty Swivel Spring Snap, 3/8" Snap Opening, 1" Strap Width, Packs of 1	$7.93	2	$15.86
	1630T33	Multipurpose 6061 Aluminum, U-Channel, 4" Base X 2" Leg, 1/2' Long	$10.08	1	$10.08
	3207K11	Super-Soft Neoprene Rubber, 1/16" Thick, 2" Wide, 36" L, Black, 10A Durometer	$11.85	1	$11.85
	9489T512	Routing Eyebolt-Not for Lifting, 316 Stainless Steel, 8-32 Thread Size, 1-1/8" Shank Length	$1.40	6	$8.40
	3937T43	EPDM Rubber Strap, 1/2" Wide, 25 ft. Length	$13.00	2	$26.00

Table 10. Cost Analysis (3 of 8)

Vendor	Part Number	Item	Cost Per Item	Quantity	Total
RobotShop	RB-And-37	#25 Single Strand-Rieted Roller Chain, 10 feet	$12.00	1	$12.00
	RB-Lyn-170	Lynxmotion Track - 2" Wide x 21 Links ~23" - TRK-01	$25.19	2	$50.38
	RB-Lyn-168	Lynxmotion Track Sprocket - 6 Tooth (Pair) SPRK-01	$7.95	1	$7.95
Amazon		Arduino UNO R3 board with DIP ATmega328P	$27.95	1	$27.95
Jameco Electronics	1	PWR SPLY,SW,TBL,REG,12V@5A,F2	$17.95	1	$17.95
	2184341	ENCODER,ROTARY,FLAT,11 MM,	$2.25	1	$2.25
McMaster-Carr	8975K87	Multipurpose 6061 Aluminum, Rectangular Bar, 1/4" X 3", 1' Long	$7.46	2	$14.92
	88225K61	Elastic Fabric, .035" Thick, 1/4" Wide, 36 ft/RL, Black, rolls of 36	$5.85	2	$11.70
Misumi	MTSFJL10	Resin Lead Screw Nuts	$13.67	2	$27.34
	MTSTR10-160-MC3	Screw Thread	$13.87	1	$13.87
	MTSTL10-160-MC3	Screw Thread	$13.87	1	$13.87

Table 11. Cost Analysis (4 of 8)

Vendor	Part Number	Item	Cost Per Item	Quantity	Total
Pololu	1591	499:1 Metal Gearmotor 25Dx58L mm	$19.95	1	$19.95
	1102	19:1 Metal Gearmotor 37Dx52L mm	$24.95	1	$24.95
	69	Tamiya 70103 Universal Gearbox Kit	$7.59	1	$7.59
	1213	Dual MC33926 Motor Driver Carrier	$29.95	1	$29.95
	713	TB6612FNG Dual Motor Driver Carrier	$4.95	1	$4.95
Cal Poly		Report CVR CLIP 60	$11.80	1	$11.80
McMaster-Carr	2737T3	Finished-Bore Sprocket for ANSI Roller Chain, for #25 Chain, 1/4" Pitch, 11 Teeth, 1/4" Bore	$9.09	1	$9.09
RadioShack		Pk100 Flat Washers	2.24	1	$2.24
Home Depot		Metric Flat Washer 6 Zinc	0.5	1	$0.50
		Machine Screw Round Head 1/4'-20x3/4"	1.18	1	$1.18
		Metric Socket Cap Screw M3-.5x10MM Zinc	0.45	1	$0.45
		Loctite 242 Blue Threadlocker	6.47	1	$6.47
Miners Ace Hardware		Fasteners	0.28	16	$4.48
Home Depot		Loctite 2G Plastix Bonder	3.77	1	$3.77
Home Depot		36"x3/8" Round Rod Aluminum	5.97	1	$5.97
		48"x1"x1/8" Aluminum Flat Bar	9.21	1	$9.21
		2" Dbl. Wide Mending Plate Zinc 4Pk	3.22	1	$3.22
Home Depot		Sheet Screw	1.18	1	$1.18

Table 12. Cost Analysis (5 of 8)

Vendor	Part Number	Item	Cost Per Item	Quantity	Total
Miners Ace Hardware		Fasteners	0.16	2	$0.32
		Fasteners	1.04	4	$4.16
		Fasteners	0.08	30	$2.40
		Fasteners	0.17	4	$0.68
		Fasteners	0.23	8	$1.84
		Clamp Half 3/4' W/ Nail 10Pk	2.99	1	$2.99
		Roller Patio DR13126 CD2	8.99	1	$8.99
		Clip Vinyl Coated 1"	1.29	6	$7.74
		Clip Vinyl Coated 3/4"	1.29	6	$7.74
Miners Ace Hardware		Fasteners	0.09	4	$0.36
		Fasteners	0.09	4	$0.36
		Fasteners	2.52	1	$2.52
		Fasteners	0.75	6	$4.50
		Clip Vinyl Coated 3/4"	1.29	1	$1.29
Miners Ace Hardware		Fasteners	0.6	1	$0.60
		Fasteners	0.25	1	$0.25
		Fasteners	0.28	1	$0.28
		Fasteners	0.25	1	$0.25
		Fasteners	0.27	1	$0.27
		Fasteners	0.27	1	$0.27
		Fasteners	0.25	1	$0.25

Table 13. Cost Analysis (6 of 8)

Vendor	Part Number	Item	Cost Per Item	Quantity	Total
Home Depot		Fiberglass Landscape Edging	29.97	1	$29.97
Home Depot		Magnet Swing hook 65# Pull 1Pc	9.97	1	$9.97
		Magnet Disc Neodymium .7x.11 3Pk	7.96	1	$7.96
		Sheet Metal Zinc 26 Ga 12x18	4.97	1	$4.97
Miners Ace Hardware		Tube Round Brass 12x3/16"	1.79	1	$1.79
		Fasteners	0.21	2	$0.42
		Fasteners	0.28	2	$0.56
		Fasteners	0.29	2	$0.58
Home Depot		Magnet Disc Neodymium .7x.11 3Pk	7.96	3	$23.88
Home Depot		Gorilla 12 Yard Heavy Duty Duct Tape	4.97	1	$4.97
		8' Vinyl Arch Corner Bead	2.75	2	$5.50
RadioShack		6' USB 2.0 Cable	20.69	1	$20.69
		90' 322 Solid UL	7.64	1	$7.64
		45' 318 STRND UL	7.19	1	$7.19
Home Depot		36"x1/4" Round Rod Aluminum	4.21	1	$4.21
		48"x3/4"x1/8" Aluminum Flat Bar	5.72	2	$11.44
		8' Black UV RSST Double Lock Cable Tie 100Pk	6.47	1	$6.47
		Quick Color Gloss Black Spray	0.97	1	$0.97
Beverly's		Spray Adhesive Clear 11oz	8.39	1	$8.39
		Foam Board 32x40in White	6.99	1	$6.99
		Easel Rust 11in	9.99	1	$9.99

Table 14. Cost Analysis (7 of 8)

Vendor	Part Number	Item	Cost Per Item	Quantity	Total
Amazon		Nylon 6/6 Rectangular Bar, Opaque Black, Standard Tolerance, UL 94V 2, 1/8" Thickness, 11/2" Width, 1' Length	$5.86	4	$23.44
Amazon		Nylon 6/6 Rectangular Bar, Opaque Black, Standard Tolerance, UL 94V 2, 1/8" Thickness, 11/2" Width, 1' Length	$4.74	7	$33.18
McMaster-Carr	8981K63	Medium-Strength Neoprene Rubber, 3/32" Thickness, 6" W, 36" L, Black, 80A Durometer, Plain Back	$13.90	1	$13.90
McMaster-Carr	98863A531	Type 316 Stainless Steel Fully Threaded Stud, M3 Thread, 0.5MM Pitch, 25MM Long, Packs of 5	$5.65	1	$5.65
	89535K86	Multipurpose 304/304L Stainless Steel Rod, 5/16" Diameter, 1' Long	$3.09	1	$3.09
Misumi	MTSFJR10	Resin Lead Screw Nuts	$13.67	1	$13.67
McMaster-Carr	8975K87	Multipurpose 6061 Aluminum, Rectangular Bar, 1/4" X 3", 1' Long	$7.46	2	$14.92
	88225K61	Elastic Fabric, .035" Thick, 1/4" Wide, 36 ft/RL, Black, Rolls of 36	$5.85	2	$11.70
Misumi	MTSFJL10	Resin Lead Screw Nuts	$13.67	2	$27.34
	MTSTR10-160-MC3	Screw Thread	$13.87	1	$13.87
	MTSTL10-160-MC3	Screw Thread	$13.87	1	$13.87
RobotShop	RB-Sct-255	Aluminum Beam 3.08" (2Pk)	$2.81	40	$112.40
	RB_And-37	#25 Single Strand-Riveted Roller Chain, 10 feet	$12.00	1	$12.00
McMaster-Carr	5448T5	Metric 932 Bronze Flanged Sleeve Bearing, for 10MM Shaft Diameter, 13MM OD, 10MM Length	$3.72	2	$7.44

Table 15. Cost Analysis (8 of 8)

Vendor	Part Number	Item	Cost Per Item	Quantity	Total
McMaster-Carr	90128A054	Zinc-Plated Alloy Steel Socket Head Cap Screw, 2-56 Thread, 5/8" Length, Packs of 25	$6.15	3	$18.45
	90480A003	Low-Strength Steel Hex Nut, Zinc Plated, 2-56 Thread Size, 3/16" WD, 1/16" HT, Packs of 100	$0.90	1	$0.90
	96082A100	Brass Two-Piece Press-Fit Tubular Rivet, 3/16" Diameter, Packs of 10	$3.97	1	$3.97
	93330A250	Aluminum Female Threaded Round Standoff, 1/8" OD, 3/8" Length, 2-56 Screw Size	$0.70	60	$42.00
McMaster-Carr	1630T36	Multipurpose 6061 Aluminum, U-Channel, 5" Base X 2-3/4" Leg, 1/2' Long	$16.42	1	$16.42
McMaster-Carr	57485K23	Set Screw Shaft Collar, for 6 mm Diameter, Type 303 Stainless Steel	$4.95	2	$9.90
Misumi	MTSTR10-160-MC3-MQ4	Screw Thread	$15.27	1	$15.27
	GEABS0.5-24-3-B-3-KC90	Super Gear	$11.64	1	$11.64
	GEABS0.5-36-3-B-4	Super Gear	$8.80	1	$8.80
Pololu	2676	Pololu 25D Metal Gearmotor Bracket Pair	$7.45	1	$7.45
		Total Cost of Prototype & Testing (Taxes and Shipping not Included)	$1,338.03		
		Total Cost of Prototype (Taxes and Shipping not Included)	$907.85		

Our initial goal was to be able to keep the prototype at a cost of $400 or less. Due to all the requirements that had to be taken into consideration, such as the amount of precision required from the system, we had to make choices between keeping costs at a minimum, and providing the best possible product at a higher but still reasonable price. There are some parts that could be made cheaper if we manufactured them ourselves, however, one of the requirements is that the parts be off the shelf, so that we can make our product open source and it can be easily replicated. Similarly, some cheaper parts can be found that satisfy the cost requirement, but we would have to sacrifice the precision provided by the system, which we consider to have a higher priority than the price. Astronomers will need to capture the correct and desired images from the diffraction grating system at any given time. Because no other product has allowed them to simplify the continuous analysis of binary stars, it is important for them to have a reliable system which they can use without worrying about not obtaining accurate results. Therefore, we propose a system which cost $907.85 before taxes and shipping, and that can be both precise and built by using off the shelf parts.

Material Selection

In selecting the material for each aspect of our design we took into account price, weight, corrosion, yield strength and application. We chose to use aluminum for most of the parts on the support frame for the diffraction grating as well as the scissors mechanism because it is lightweight and does not corrode. It is important that the support frame is light-weight in order to reduce the moment and it is also important to consider corrosion because the entire system will be operator outdoors.

We chose to use neoprene for the fastening fabric that is in direct contact with the telescope because it has a high coefficient of friction so it will not slide off the telescope and it is flexible so it will fit nicely around the telescope. Also, it is a soft, yet sturdy material so it will hold the railing in place and not damage the surface of the telescope.

We chose to use a metal sprocket gear and chain belt to move the carriage around the telescope because the belt needed to be strong and have low interference with the sprocket. After testing, it was determined that the metal belt was better to use than the plastic belt because it had a smaller pitch and performed better under high tension. The plastic belt and sprocket combo was difficult to rotate around the telescope when tension was applied to the belt.

Geometry Selection

When determining the geometry of each component of our design it was dependent on the load that would be applied to it and we tried to make it as compact as possible so it can be easily stored. The thickness of the support beams, scissors, and other load bearing components were determined analytically using static and kinetic diagrams.

Another influence in our geometry design were stock parts. We tried to use as many stock parts as we could, so that our design could easily be replicated by someone with no engineering background. This caused some components to be a little pricier, and in the end we decided that some light machining would be acceptable (such as drilling holes for machine bolts).

The carriage geometry was designed in order to be as efficient as possible with our space. There are several bulky gears, motors, and pulleys attached to the carriage that caused it to be as big as it is. We also designed it to be as wide as it is so that it provides a counter torque to the grating that is attached to it.

The geometry was also determined by assembly constraints. For instance, the dimensions of the support frame for the scissors-grating mechanism depends on the diameter of the telescope and the height of the carriage. The frame had to be wider than the diameter of the telescope otherwise it would ruin the diffraction patterns. Similarly, the distance between the front rod and the front guide rail is directly related to the height of the carriage. The purpose of the distance between the rod and guide rail is to offset the diffraction grating from where it attaches to the carriage so that it is suspended over the telescope lens. Therefore, if the carriage height increases, so does that distance.

Software Design

The Automatic Diffraction Grating Project does not require an overly complicated software system to run it. Essentially consisting of one microcontroller, three motors, and one serial communication line, this project is easy to model and control. A basic PID motor controller will be used in conjunction with rotary encoders to control the scissor mechanism as well as the carriage's position on the outside of the telescope. The flip up mechanism does not require a closed loop control scheme, but can easily be operated using a single motor and a pair of limit switches. Finally, a single control hub will handle communication between Orion Observatory's warm room, and the Automatic Diffraction Grating System. A flowchart of this control scheme can be found in Figure 30.

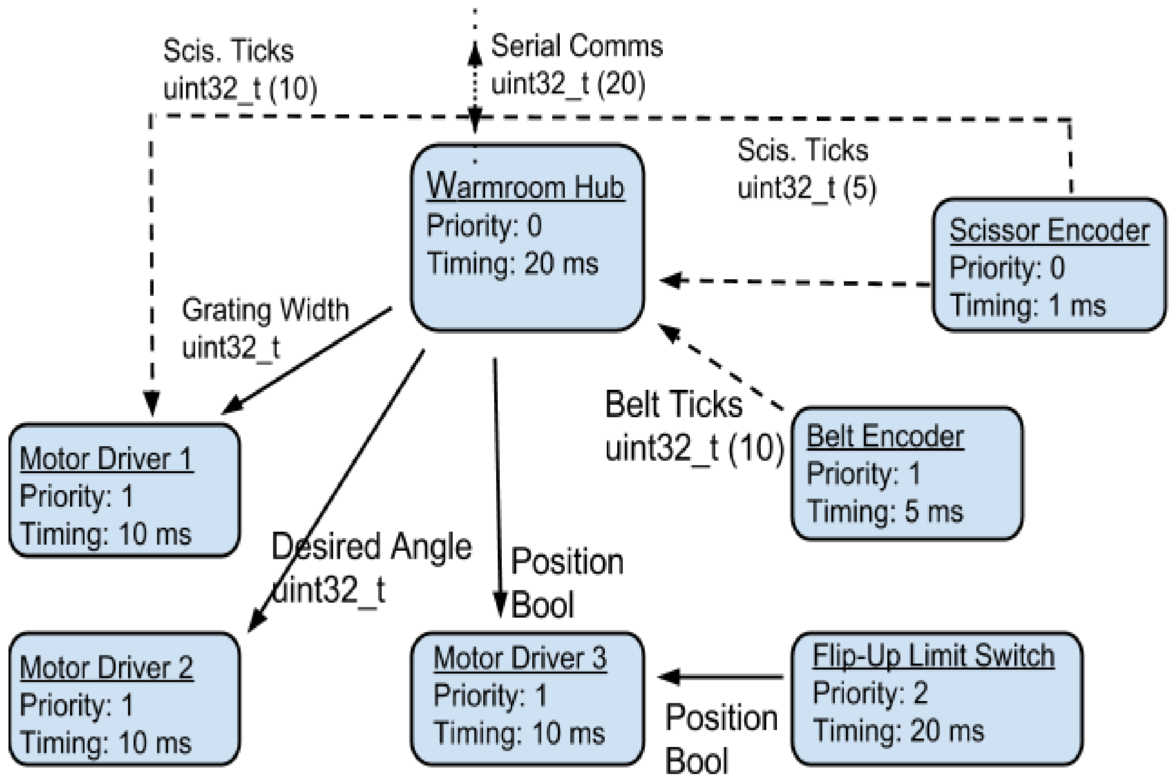


Figure 30. Automatic Diffraction Grating Task Diagram. 0 = High Priority. (StarT.E.K., 02/01/2015)

Manufacturing

Because one of our design requirements is to have parts that are off the shelf, there is little to no manufacturing needed for our design. Most pieces are stock parts that can be ordered online or picked up at your local hardware store. We do, however, have a few parts that need holes drilled into them. The following parts need holes and their schematics are detailed in Appendix B.

- Support Beams for grating frame
- Angle brackets that attach the grating frame to the carriage
- Carriage walls that hold everything together
- Buckle that attaches the sleeve and belt to the telescope
- Motor mount plate for the scissor mechanism
- Front and Back rods for the grating support frame
- Grating Rulers

Another component of the design that needs to be built is the sleeve that wraps around the telescope. The sleeve needs to be sewn and combined with the guide rails. These specifications can be found in Appendix B as well.

Safety Considerations

Three low to moderate hazards have been identified in relation to using and operating the Automatic Diffraction Grating. First, as with all automatic machinery, when operating the automatic diffraction grating make sure there are no objects within the robot's work zone. StarT.E.K. strongly recommends that no one be present within a 2 foot radius around the telescope. The system is also designed to be operated remotely, and we recommend that no individuals be closer than 5 feet from the telescope during its unsupervised operation.

Secondly, there are several potential pinching possibilities when the scissors are expanding and compressing, when the gear belt is in use, and when the flip up mechanism is in use. Therefore, StarT.E.K. strongly advises against attempting to come within 2 feet of the telescope during operation, and strongly warns against attempting to personally handle the Automatic Diffraction Grating. In an effort to counter this possibility, most of the parts are rounded or chamfered so that users are not cut or injured during setup.

Finally, the Automatic Diffraction Grating will operate on standard 110V AC electrical power. If an individual were to attempt to remove all protective coverings and tamper with the power systems of the device, there is a possibility of electrocution.

Other major safety issues have yet to be identified for this project. The diffraction grating is lightweight and will be mounted low enough that the danger of it falling and causing injury is minimal. There are no blades, projectiles, or unusually high power sources on the system, and no means of storing energy or dangerous chemicals. While the Automatic Diffraction Grating project is not deemed to be hazardous, it will nonetheless be closely examined and thoroughly examined during the testing phase of the project.

Maintenance and Repair Considerations

As this system is a lightweight robotic system that will be operating outdoors, there are two primary concerns with respect to maintenance and Repair.

First, corrosion and contamination have the potential to become major factors affecting the life of the grating system. While care is usually taken when operating the telescope, dew, cold, and light rain are all commonplace. All of the components of the diffraction grating have been selected for their corrosion resistance. Aluminum, Stainless steel, and Zinc plated materials are only the beginning of the list. Protective jackets and covers have also been, and are continuing to be added, helping to shield the internal systems from water, wind, and dirt. These systems are not perfect however, and weekly disassembly and cleaning should be a part of the Diffraction Grating maintenance cycle.

The other major concern is fatigue and wear. While these considerations have been taken into account in the design of this system, automatically running machines are easy to forget, and allowed to wear down. To counter this, it is recommended that the Automatic Diffraction Grating be examined before every use. In particular, the drivetrain, the scissor mechanism hinges, and the tensioned chains are all potential sources of problems if allowed to wear down or become contaminated. These factors will be watched closely during testing, and anything that has the potential to become an issue will be noted and addressed.

Chapter 5: Product Realization

Introduction

The primary intent of this project is to be produced with off-the -shelf parts, with minimal machining or specialized equipment required in order to be easily replicated. To this end, the construction and assembly of the Automatic Diffraction Grating consisted of a small number of simple drilling operations, followed by the main assembly process.

A complete manufacturing drawing for each part can be seen in Appendix B.

Manufacturing Process

The following components required drilling or tapping operations:

Table 16. Table of Manufacturing Process

Component	Quantity	Drill	Tap
Stainless Steel Guide Rod	1	Yes	Yes
Nylon Guide Rod	1	Yes	Yes
Vertical Aluminum Frame Bar	2	Yes	No
Aluminum Crossbar	2	Yes	Yes
Carriage Plate (Front)	1	Yes	No
Carriage Plate (Back)	1	Yes	No
Carriage Plate (Top)	1	Yes	No
Shaft Bracket	1	Yes	No

Each of these operations were designed to be simple enough to conduct with tools available in a small shop or garage. In order to demonstrate this, each of the required operations was performed on the Cal Poly campus, by team StarT.E.K..

Aluminum Carriage Plates

The drilling of each of the carriage plates was performed using the Mustang '60 mill (Figure 31). This was done due to the ease of using a mill to drill a pattern of holes at various locations, with precision. These holes are possible to create using a hand drill; however, they would be more difficult.

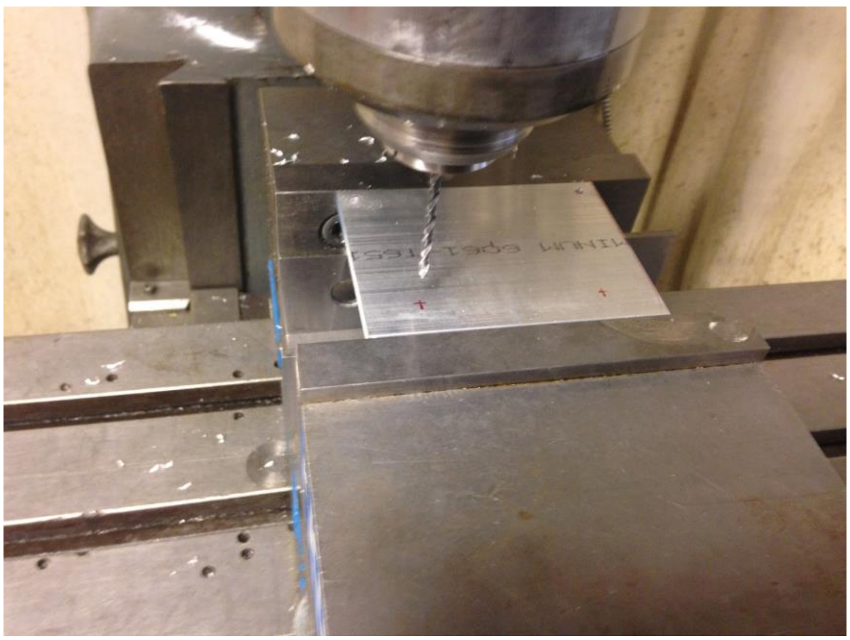


Figure 31. Drilling Holes for Carriage Frame on a Mill

Aluminum Flip-up Frame Bars

The aluminum bars that make up the frame supporting the diffraction grating were cut to length on the vertical band saw. Because these parts had fewer holes to drill, they were carefully marked by hand, and drilled using a drill press. The end holes on the aluminum crossbar were tapped by hand.

Guide Rods

The most difficult part to manufacture was the stainless steel guide rod that transmits the torque needed to flip up the diffraction grating. This component needed to be trimmed to length, drilled through each end, and tapped. In our case, this was done on the Mustang '60 lathe, with a parting, drilling and tapping operation respectively.

Admittedly, these operations would be difficult to perform without a lathe. The parting would have to be done with a bandsaw or - worst case scenario - bolt cutters. The drilling and tapping operations would not be significantly different; however, the bits and taps typically available to consumers are made with high speed steel, which will wear down quickly when working with stainless steel. Stainless steel itself is unforgiving to work with, as it tends to quickly work harden.

The nylon guide rod was also machined on the lathe; however, there would be no difficulty in machining this part with hand tools.

Shaft Bracket

The shaft bracket was a late addition to the design, added simply to keep the spur gears driving the lead screws in alignment. In true do-it-yourself fashion, the stock bracket for this part had holes drilled in it by hand.

Assembly Process

The final steps for putting together the Automatic Diffraction Grating were divided by subsystem. First, the carriage was assembled and tested, as it was the central subsystem within the assembly. Next, the scissor mechanism and supporting frame were assembled, with great care being taken to maintain and improve the precision and quality of the scissor mechanism, the most critical of the subsystems. Finally, the belt and rail systems were assembled in stages, paralleling the requirements and findings of the testing procedures.

Carriage Subsystem

The first subsystem to be assembled was the carriage subsystem. As with many of the Automatic Diffraction Grating's subsystems, the carriage went through several iterations in both design and construction. The assembly steps discussed here outline the general assembly. This assembly took place in the following steps:

- First, the aluminum standoffs were bolted to the front and back aluminum plates (Figure 32). This forms the basic structure of the carriage. The machine screws that hold the front carriage plate also passed through the triangle brackets that would support the top plate and flip up mechanism.
    - The wheels that allow the carriage to roll on the outside of the telescope were fitted over the lower standoffs.
    - Spacers were initially used on the shafts supporting the wheels, but were later removed to save weight.

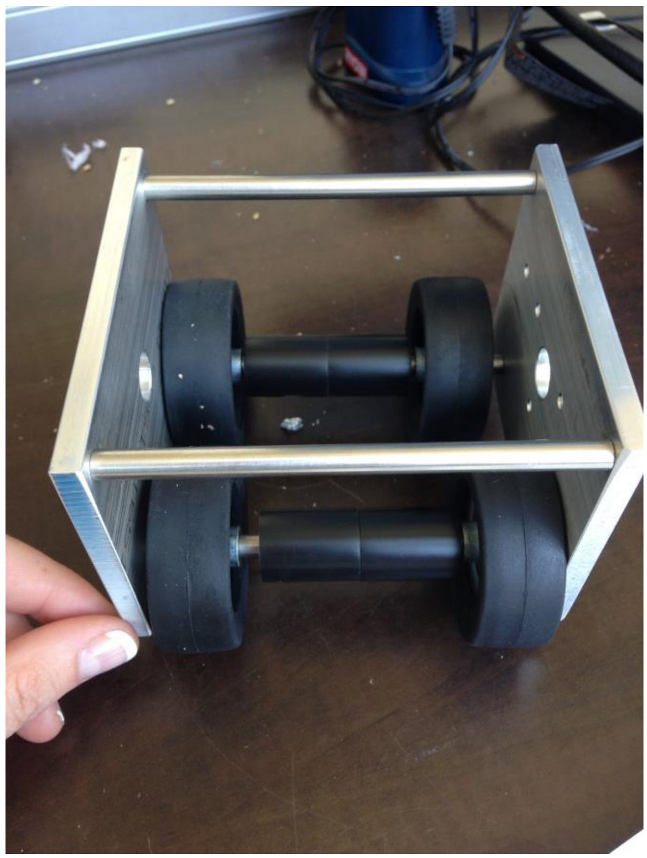


Figure 32. Initial Assembly of Carriage

- Second, the main drive motor was bolted to the front carriage plate.
- The main drive shaft was assembled as it was inserted into the carriage, passing through the back carriage plate and the two sprocket gears before being inserted into the shaft coupler that connects the main shaft to the drive motor. The back end of the drive shaft was then locked in place using a spacer and a shaft collar.
- Over the course of testing, it was determined that guide wheels or idlers were necessary on the upper shafts of the carriage, in order to keep the drive chains moving smoothly, and to keep them in alignment. These components were then added as soon as they were available.
- Once the locations of each component was finalized, the bolts were secured in place using loctite.

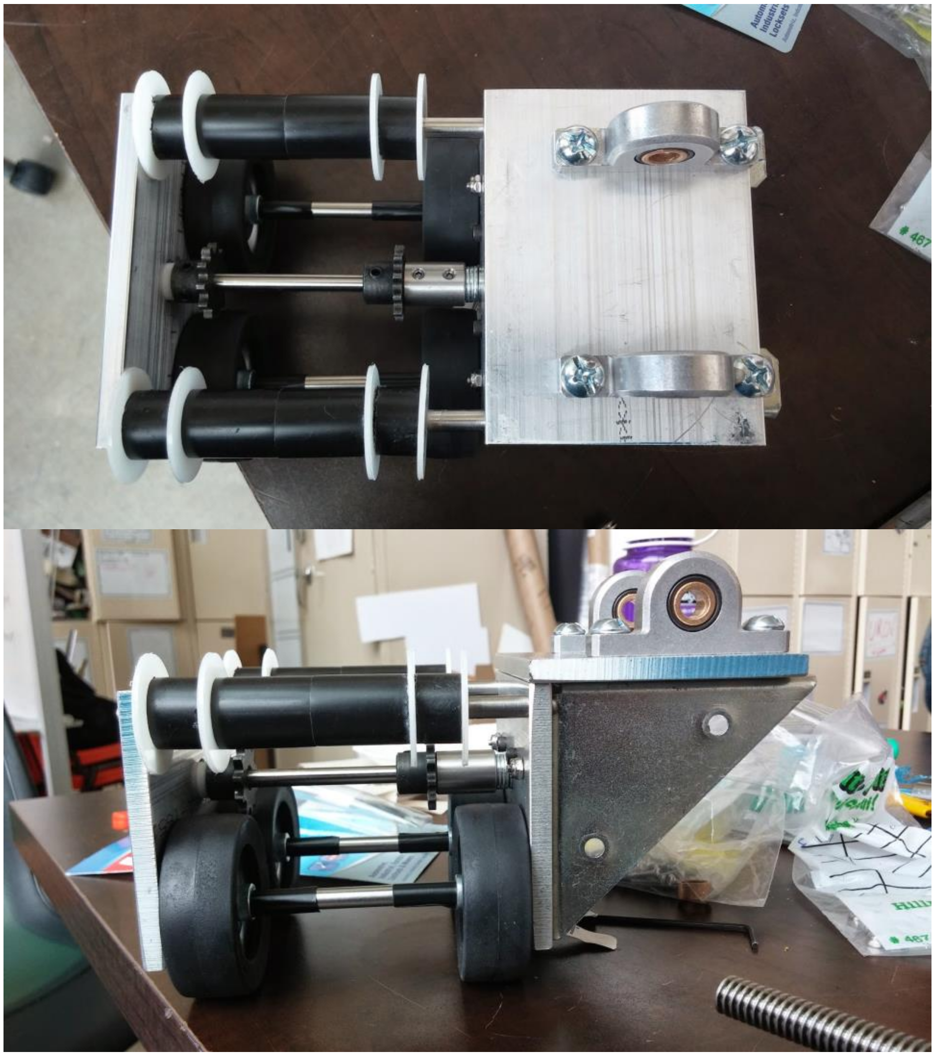


Figure 33. Carriage Assembly

- The top aluminum carriage plate was later removed to facilitate the assembly of the flip up mechanism, as well as to conserve weight.
- Initially, the carriage had an open base as seen in Figure 33 above, but after much testing and iteration of the system that holds the carriage to the telescope, two brackets were mounted to the bottom wheel shafts. These brackets were used to fasten 20 magnets to the bottom of the carriage which would be attracted to a metal strip in the sleeve feature. The wheel shafts were pushed through the holes on the brackets and the two brackets were bolted together back to back.
- Magnets were generously placed on each side of the brackets and stacked until just millimeters above the surface.

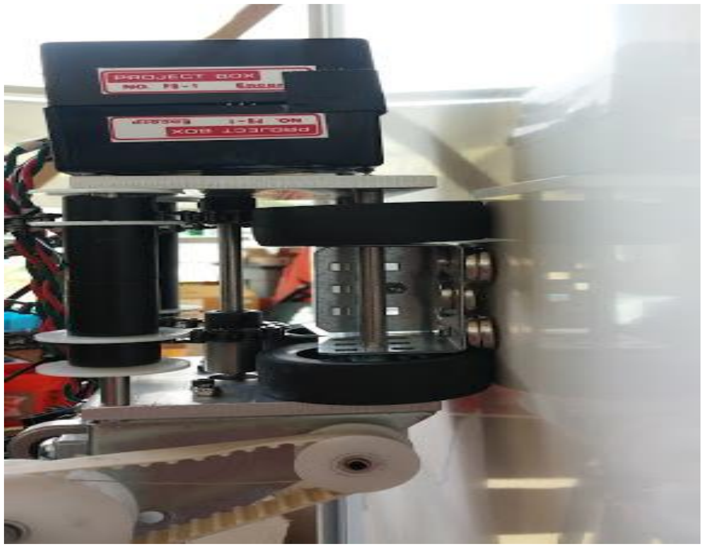


Figure 34. Carriage Assembly with Magnets and Electrical Box

Diffraction Grating Subsystem and Scissor Mechanism

The second major subsystem to be assembled was the scissor mechanism and the aluminum frame supporting it. Of all the subsystems constructed for the Automatic Diffraction Grating project, this one underwent the most iteration and redesign, eventually being constructed out of entirely different materials than originally planned.

- First, we assembled the aluminum frame by screwing the guide rods to each end of the aluminum side supports using #4-32 screws. Before you screw the aluminum rod in, slide the larger pulley wheel on the shaft.
- Then, we inserted the bronze through bearings in the specified bores of the side supports and slid the drive screws through the bearings. Some filing might be necessary to allow the drive screws to slide in smoothly. Ensure that the drive screws can freely spin.
- The drive bearings were screwed onto each drive screw and evenly spaced from the inside end.
- Next, we slid the smaller spur gear and the gear train bracket onto the drive screw connecting rod. Note that it is not necessary to tighten the set screw until you verify the gear position with the gear mounted to the motor.
- Then we screwed the connecting rod into both drive screws and secured it with Loctite.
- A third bearing was screwed onto the end of the right drive screw until it reached the edge of the support beam and loctited into place. The combination of this bearing and the gear train bracket keeps the drive screw mechanism from sliding out of place.
- From here, we assembled the larger spur gear to the motor shaft and tightened the set screw into place.
- Next, the motor was mounted to the motor bracket and the bracket mounted to the motor support (or cross bar).

- The cross bar was attached to the side supports so that the motor is parallel with the drive screws. Because of the manner in which the motor attaches to the motor mount, the cross beam is slightly tilted.
- Then it was time to mesh the two gears together and tighten the set screw on the smaller gear.

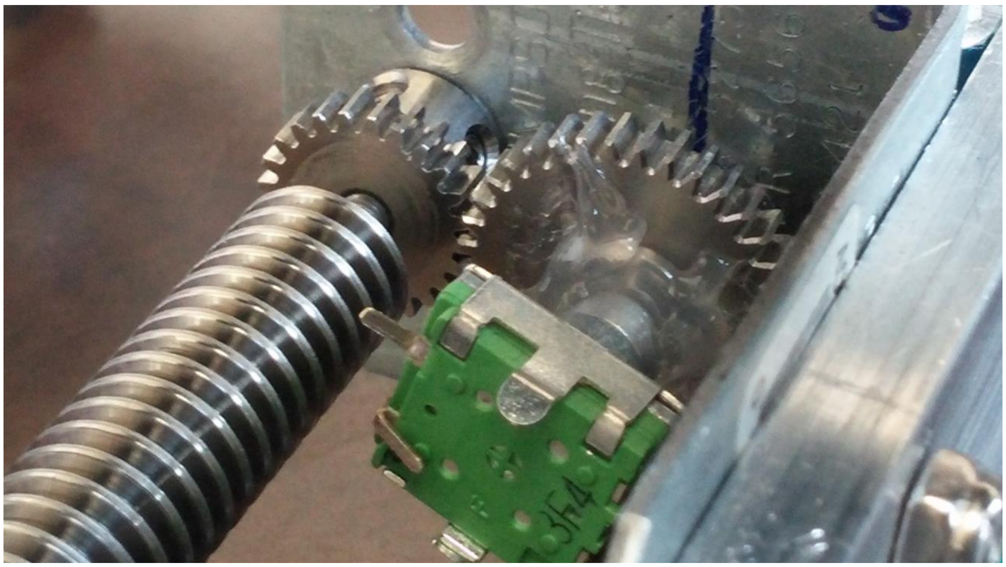


Figure 35. The Spur Gear Set Driving the Scissors

- Next, the scissors were assembled. After many iterations which can be seen in Chapter 6, we settled on ABS plastic LEGOS beams as our scissors links. We used LEGO Technic Pins to hold the beams together. The beams were connected on each top, bottom, and middle holes and there were 20 beams on each side of the grating to create 10 “x’s”. The bottom pin connection on the 4th and 7th scissor segments do not need to be connected by LEGO pins.
- From here, we squeezed the scissor clamps around the drive bearings and bolted the scissors using the open holes to the clamps using a 1.5 inch bolt, washer and nut. We did this on both sides, however, there is no bearing on the far side, which allows the clamp to rest loosely on the nylon rod.

Figure 36. The Assembled Scissors Mounted to the Diffraction Grating.

- Once both scissors were assembled and mounted to the support frame, we could attach the grating. Using the Loctite plastics bonding system, we epoxied the gratings equally spaced onto the inner scissors beam. We followed the instructions on the box for optimum adhesion. We found that the easiest way to ensure equal spaced gratings was to fully extend the scissors and secure them in place. Then ram the grating bar flush against the corner between scissors (there will be a corner to rest on) and apply the epoxy.
- Lastly, we laid the u-channel over the scissors closest to the carriage and lightly zip tied them down. We were careful not to add any strain on the scissors themselves.

Flip Up Mechanism

The third major subsystem to be assembled was the flip up mechanism. This was the most straightforward aspect of our design and the only part that worked exactly as designed and did not require any re-engineering.

- First of all, the large pulley wheel was already on the aluminum guide rod.
- So then we just had to attach the smaller pulley to the motor shaft. Unfortunately there was about a 1mm clearance between the motor shaft and the pulley wheel bore so the pulley would not stay in contact with the shaft by itself. Using a bolt cutter or chop saw, we cut a 1 inch length piece from the bronze 4mm I.D. hollow shaft as a spacer between the motor and the pulley. We then used the set screw to hold both in place. Loctite was also helpful in securing all three pieces.

- The hardest part was getting the timing belt over both pulley wheels. We were successful when putting it on the larger wheel first.

Sleeve, Rail and Buckle Subsystem

The sleeve was originally designed to protect the surface of the telescope and keep it from being damaged from our device. However, through iterations and testing it become a crucial part to our design. It now not only acts as a protection for the telescope, but contributes to keeping the carriage aligned and prevents it from falling off the telescope.

- We began by cutting the arched drywall corner bead to the length of the neoprene (36”).
- Then we wrapped it around the telescope and used gorilla tape to cover the spacings between the tabs and reinforce the wall.
- Next, we began sewing the arched corner to the neoprene itself by sewing the bottom edge on each end of the neoprene with the wall (the gorilla taped edge) facing the center. We kept the inner walls 4” apart so the carriage could fit between them.

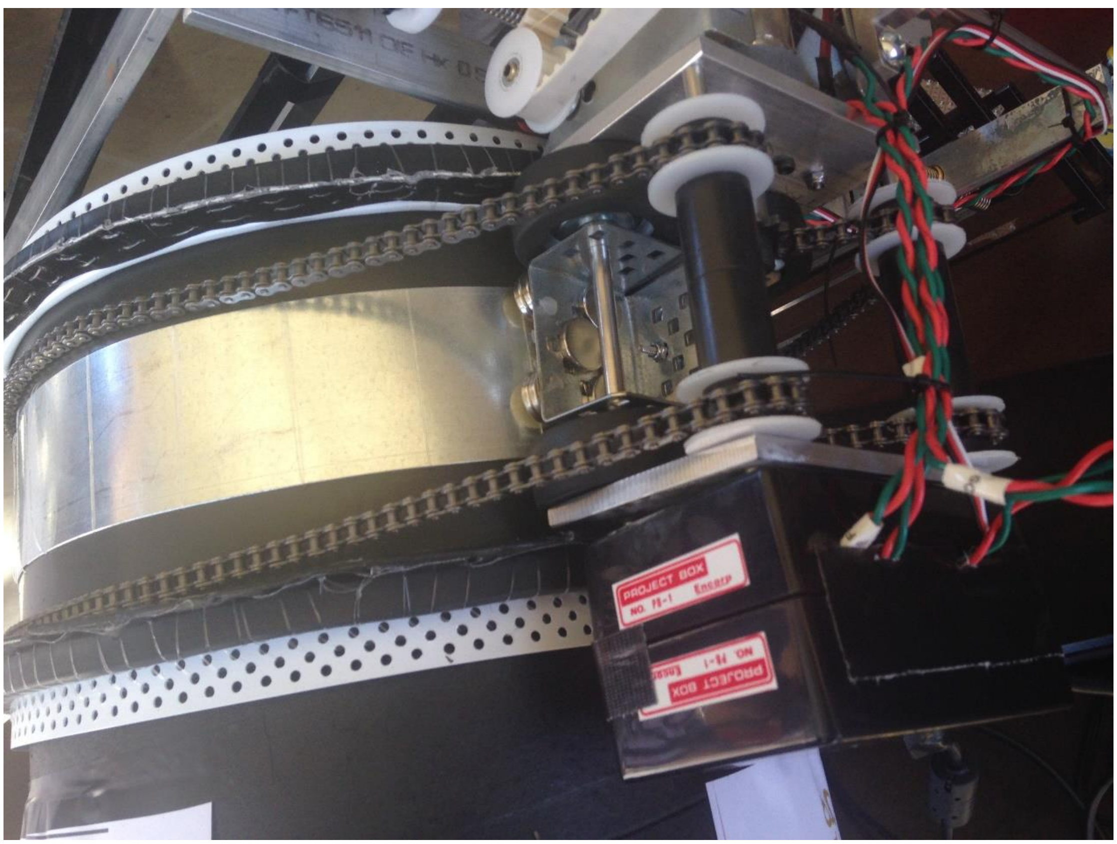


Figure 37. The Width of the Sleeve Fitted to the Carriage.

- Then, we stacked three rubber cords on the outside of each taped wall (on top of the corner edge sewed to the neoprene), and sewed them into place. This served as reinforcement for the wall.

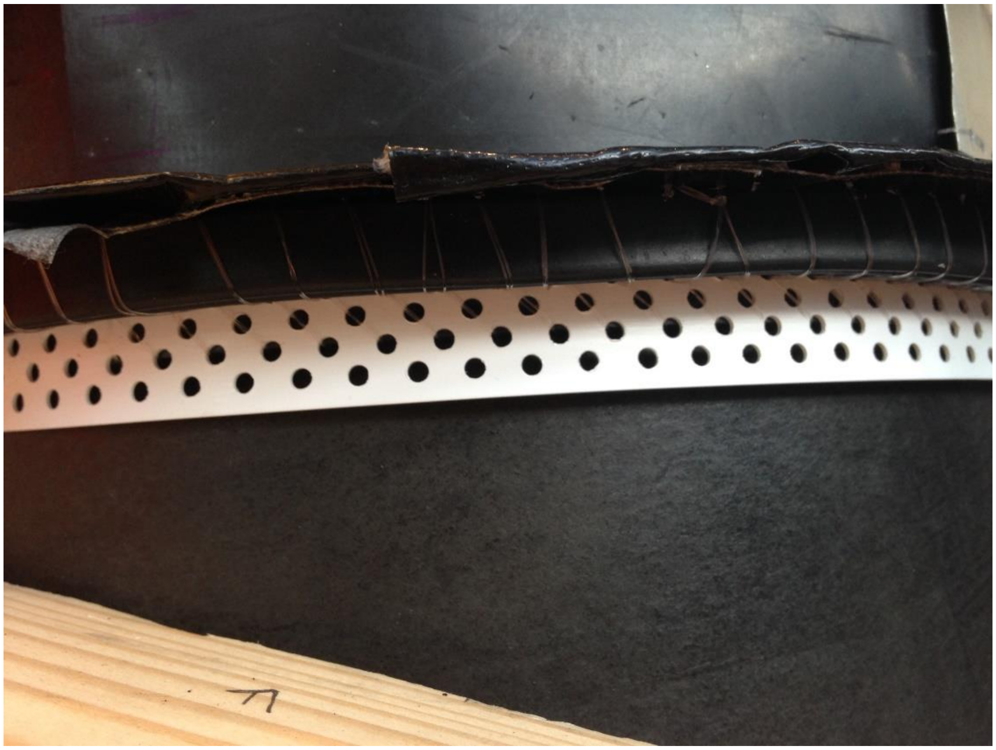


Figure 38. Rubber Rails Reinforcing the Guide Rails.

- Then we trimmed one of the rails to just above the top of the stacked rubber cords. This rail was for the side of the carriage with the triangle brackets and motor.
- Then we cut a metal strip out of the sheet metal the width of the outer distance between the wheels (3.5”). We then punched out ⅛” holes along both edges of the metal strip and straight down the middle, about 1” apart from each other.

Figure 39. Metal Sheet with Hole Punches

- Next, we sewed it in the middle of the neoprene, equally spaced between the rails.
- Lastly, we attached the springs through the center holes in the arched corner. These will attach to the buckle.
- The buckle is used to keep the chains and neoprene from sliding around or off of the telescope. All one would need to do is screw in the eyelet hooks into the side of the u-channel. This is where the hooks connect to. Unfortunately, we never got a chance to build the buckle because our design was never tested on the actual telescope. For testing purposes we screwed the chains into the cardboard test tube that was reinforced with a fiber-glass inner ring.

Recommendations for Future Manufacturing

Most of these recommendations were mentioned in the manufacturing and assembly sections previously, but are summarized below.

- All of the drilling is manageable to do with a simple hand drill, but it is necessary to be as precise as possible when measuring the locations.
- We broke 2 taps when tapping the small holes on the ends of the stainless steel guide rods due to work hardening. We recommend going very slow and using tapping fluid. Also, be sure to back out of the tap every so often to clear out chips.
- When attaching the timing belt, put the belt on the larger pulley first before stretching it over the smaller one.
- When sewing the rubber cords for the railing, it is best to sew in one cord at a time and continually stack them on top of each other because it provides the most stability.
- When mounting the grating on the scissors bars, we suggest extending the scissors to their maximum position. This results in a corner created at one end of the grating bar. Place the grating against this corner as you apply the epoxy and you will ensure equidistance between each grating.

Figure 40. Fully Assembled Grating

Chapter 6: Design Verification

Initial Design Verification Plan

Properly testing the Automatic Diffraction Grating will involve confirming that the system meets several specific goals and functions. Because of this, the testing phase of this project has been broken into three separate categories which are described below.

Ideally all of these tests would be performed to ensure a fully functioning design; however, several portions of the quality check were eventually passed over in favor of critical functionality testing.

Area 1: Quality check and Functionality Testing

The first area of testing will take place immediately after the construction of the project, and is designed to ensure proper assembly and full functionality.

Quality Check

A major factor involved in the success of the Adjustable Diffraction Grating is its precision. Because of the large distances and the microscopic physical properties involved such as the wavelength of light, and the target angle for measurement, high precision is required in order to maintain accuracy. Therefore, the final assembly must be checked for accuracy.

The current tolerance in the location of each bar is ± 0.015”. The main way that this tolerance will be enforced is the ability of the system to predict where the edges of the bars are with respect to the overall grating pattern. This is separate from encoder calibration, and will ensure that the assembly itself is of sufficient quality that a sound control system can reliably position it.

As any slack in the joints of the scissor mechanism will result in an inaccurate positioning of the bars. Therefore, the overall backlash will be limited to less than 0.010 inches, or must be repeatable so that an encoder and control system can predict the location of the scissors within 0.010 inches after repeated movements.

Properly mounting and locating the diffraction bars is also a critical element in maintaining the accuracy of the system. Each bar will therefore be accurately sized to within 0.005 inches. The angle of the bars will be perpendicular to within 1 degree, and each bar will be located within 0.010 inches of its desired location on the scissor linkage.

Because the flip up mechanism and carriage location rely on accurately recording position as opposed to predicting it, these elements do not need specific quality checks, save that they are all within the specified drawing tolerances. They will however, be closely examined during calibration.

Functionality Testing

Once the quality of the parts has been confirmed, the overall functionality of the system will be tested. In order to pass this test, the entire assembly will be mounted to a mockup of the actual telescope, and each of the following actuators will be checked:

- Scissor Actuation: The scissor mechanism that adjusts the width and spacing of the bars and slots must be able to expand to the full width required (33”), and collapse to the minimum position (11” wide). The mechanism must be able to do this repeatedly, and without losing accuracy or warping in any way.
- Grating Rotation: The carriage riding around the outside of the telescope must be able to move through a full 180 degrees, while maintaining precision, and without failing. The carriage must be capable of supporting the grating in any position.
- Flip Up Mechanism: The flip up mechanism must be capable of rotating the grating from immediately in front of the telescope, through 270 degrees, to its fully stored position parallel with the telescope, and return it to the front of the telescope. The mechanism must be able to do this a total of 10 times, without warping or damaging the grating. As this movement will be controlled by limit switches rather than an encoder, no calibration is required.

Area 2: Simulation and Predictive modeling.

The second area of testing is an intermediate step between the physical check of the system, and the field tests in which the full astronomical experiments will be conducted.

As very few adjustable diffraction gratings have been constructed in history, there is little literature or data available to compare to any results we might acquire from our Automatic Diffraction Grating. Therefore team StarT.E.K., and Dr. Genet have partnered with Dave Rowe of Cal Tech to simulate the theoretical effects of the diffraction grating. Mr. Rowe is currently developing a simulator that allows various complex grating patterns to be tested. This software

is easily capable of predicting the effect of our Automatic Diffraction Grating. Therefore, in order to generate an expected behavior or baseline for this project, a range of simulated masks that the assembled Automatic Diffraction Grating creates will be inputted into Mr. Rowe's masking program, and the results recorded. These results will be used in two ways: First, the results of the simulation will be used to back calculate the incident angles of light incoming from binary stars and be compared to the expected and known values. If this mathematical proof continues to hold, the grating patterns will be deemed to be useful. Secondly, if the diffraction pattern manages to produce accurate results, the expected pattern will be used to confirm the functionality of the Automatic Diffraction Grating during field testing.

Area 3: Application.

The third area of testing involves attaching our design to the telescope itself, calibrating the system and collecting data to see if it works in a real life application.

In order to calibrate the system, our team will go to the Orion Observatory and attach our system to Dr. Genet's Celestron C-11 Telescope. We will calibrate all of the mechanical parts such as the scissor mechanism and the carriage rotation to obtain our desired accuracy of 0.015 inches, then cycle the system through it maximum ranges of motion. The success of this test will be determined by the control system's ability to return the grating to a given position with the desired accuracy. This calibration is a process which may occur upon every startup of the system; however, the Automatic Diffraction Grating must remain calibrated throughout the current session, as specified in our design specifications.

Once the system has been calibrated, "warm room control" testing will begin. In this series of tests the Automatic Diffraction grating will be remotely controlled from within the observatory's data center, and will be commanded to move to the positions and form the patterns needed to measure the separation of known binary stars. During these tests, the system must remain functional, as well as being cooperatively integrated into the telescope's existing systems. It will also be carefully monitored for its reaction to exposure to outdoor conditions, fatigue, or hidden software errors.

As sufficient data is collected, the results of capturing data with the Automatic Diffraction Grating will be compared to the data from the simulations with Dave Rowe, and the separation angles will be calculated and compared to known angles of the observed binary stars. The Automatic Diffraction Grating will then be evaluated based on the criteria listed in chapter 1.

Actual Testing Achieved

The following tests reports summarize the data collected as the actual design verification and functionality tests were conducted. Each test report summarized the testing quantity and result before going into the full test description.

As these test proceeded, it became clear that this project's scope would be limited by time such that the main goal of these tests would be to determine the feasibility of this project and these designs.

Flip Up Subsystem

Pulley Belt Flip Up Functionality

Purpose of Test

To determine the feasibility of using a pulley and belt system to flip the grating support frame off of the face of the telescope a full 90 degrees and hold its position.

Verification Quantity

General functionality.

Pass/Fail?

Pass

Test Procedure

The pulley system was assembled and the support frame was attached to the carriage through the drive belt. The system was actuated and tested for full range of motion.

Setup

The smaller pulley wheel was fastened to the shaft of the flip up motor on the carriage and the larger pulley wheel was attached to the front rod of the support frame with the scissors assembled to it. The drive belt was connected between the two pulley wheels and power leads were attached to the motor.

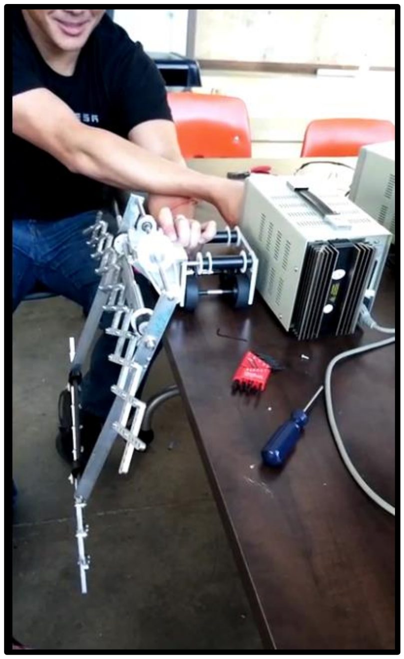


Figure 41. Pulley Test Setup

Recorded Data

Full range of motion.

Results

The system was able to flip the support frame a full 90 degrees and hold its position at any angle we actuated it to. This proved that our flip up mechanism functioned properly and was adequate enough to complete our design.

The system was tested with the aluminum rods as the scissors and passed. Now that we are actually using the ABS plastic scissors, the scissors mechanism is much lighter, so the pulley is more than adequate.

Recommendations, Design Changes and Future Steps

This system worked as intended, so there is no reason to adjust the design.

Carriage Subsystem

Drive Chain Functionality Testing

Purpose of Test

To confirm the functionality of the drive chain method for moving the carriage.

Verification Quantity

General functionality.

Pass/Fail?

Pass with modifications.

Test Procedure

While preliminary tested had already been conducted on the prototype and proof of concept models, this functionality testing was the first time the fully functional carriage and chains were strapped to a mockup of the telescope and tested as a system.

Setup

A mockup of the telescope was constructed from a 12 inch cardboard construction tube. The carriage was then mounted to the "telescope" using its two drive chains, and powered directly from a DC power supply.

Figure 42. Telescope Mockup

Once mounted, the carriage was driven repeatedly back and forth 180 degrees around the telescope. This was repeated with the telescope in various positions, starting from horizontal and incrementing until it was pointed vertically.

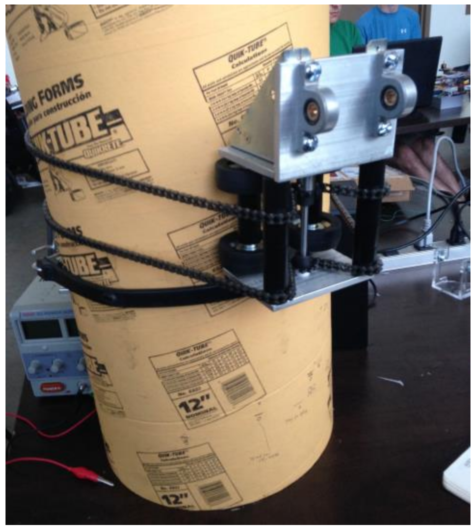


Figure 43. Carriage Testing

Recorded Data

N/A

Results

Three main findings were the result of this series of tests:

1. The drive system for the carriage works very well, as the motor is capable of smoothly moving the carriage around the telescope. However, the orientation was a much bigger issue than anticipated, requiring hugely fluctuating amounts of power, and being extremely difficult to control.
2. Guides were required to keep the chains aligned while passing over and through the carriage. We also confirmed that guide rails are needed to keep the carriage in place on the telescope. Both of these are especially true as the telescope is angled towards a vertical position.
3. Driving a DC motor over its recommended current limit will result in the burning/demagnetization/general wrecking of that DC motor. Once the motor has been "wrecked," it will operate at a fraction of its original torque.

Recommendations, Design Changes and Future Steps

The design of the carriage was modified to include guides on the rollers that the chains run over on the carriage.

Drive Chain Tension Calibration

Purpose of Test

To determine the optimal tension for the carriage's main drive chain.

Verification Quantity

Can it drive?

Optimization for minimum power draw.

Minimization of backlash.

Pass/Fail?

Passed after much fine tuning.

Test Procedure

This series of tests was conducted to determine the optimum tension to be used for driving the carriage. It was noticed that the tighter the chains, the more effort it took to drive the carriage back and forth. In contrast, the looser the chains, the more backlash present in the carriage's drive train, and - in extreme cases - the more likely the chains were to slip.

Setup

Initial ranges of tension were estimated by hand, and varied from extremely tight to very loose. For these tests, the chains were pulled to an approximate tension, and clamped in place.

Figure 44. Tension Testing Set Up

These tests revealed that the best tension was about what was needed to keep the chains barely taut. Adding a force meter, we measured the optimal force.

Recorded Data

Optimum Tension: 8.125 lbf.

Results

This force was significantly lower than the expected 13 lbf. This makes it much easier to drive, but that the chains cannot be used to hold the chain.

Recommendations, Design Changes and Future Steps

This test verified that the drive chain portion of the carriage was feasible, tunable, and functional at the specified tension.

Carriage Full Range Limits

Purpose of Test
To determine the range of motion achievable by the carriage.

Verification Quantity
Limits of motion

Pass/Fail?
Fail

Test Procedure

We mounted the fully assembled neoprene sleeve to the cardboard tube. This was our first time using the sleeve after the rails were fully sewn in and the metal strip was sewn in (rather than being clamped down). We mounted the carriage onto the sleeve and attached the chains to the buckle in the back.

Setup

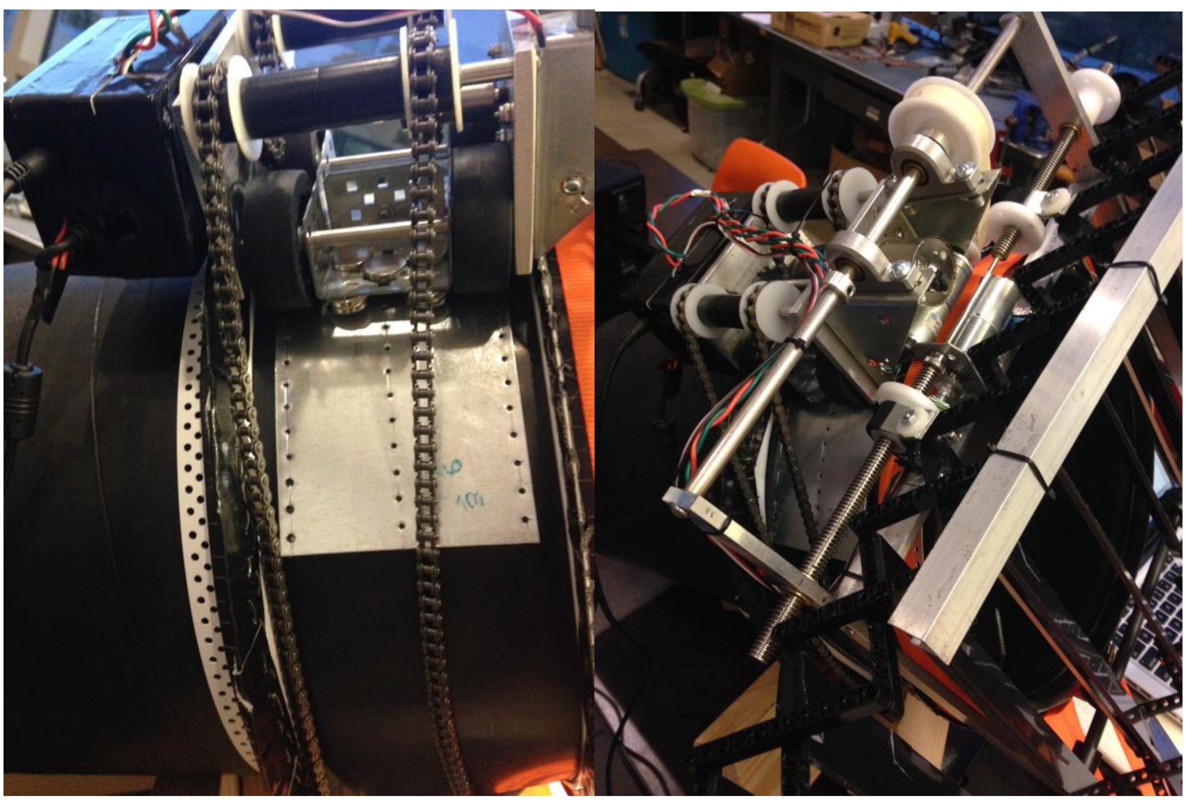


Figure 45. Carriage Testing

Recorded Data

N/A

Results

Due to the manner in which the metal sleeve was sewn onto the neoprene sleeve and the short distance between the metal and the magnets on the carriage, the metal lifted off of the neoprene slightly and came in direct contact with the magnets. This caused the rubber wheels to compress and lift off of the surface, so they did not have enough contact to move the carriage. The added friction from the magnets touching the metal kept the carriage from moving at all.

Recommendations, Design Changes and Future Steps

We did not get a chance to modify this design in the allotted time for the project, but if we had more time we would adjust the amount of magnets on the carriage and their placement on the brackets. We would also find a better way to secure the metal down so that it doesn't lift off of the neoprene. The main goal is to find the optimum distance between the magnets and the metal where the attraction is strong enough to hold the carriage on but not too close that it is in direct contact with the metal.

Sleeve and Rail Subsystem

Carriage Full Range Limits

Purpose of Test

To determine the full range of motion of the scissors system.

Verification Quantity

General full range of motion

Pass/Fail?

Pass

Test Procedure

We powered the scissors mechanism to its maxed out position and to its minimum position and measured the distance between the bars as well as the full width of the grating.

Setup

Figure 46. Scissors Full Range of Motion

Recorded Data

The maximum full width of the grating was 28.25 inches with the width between the grating being 1.5 inches. The minimum full width of the grating was 20 inches with the width between gratings being 0.75 inches.

Results

The system achieved a ratio of 2:1 for the spacing between gratings.

Recommendations, Design Changes and Future Steps

We don't recommend using the grating at its maximum or minimum widths because they are the extreme values and can cause stress on the motor or it could damage other features of the system.

L-Shaped Rails + Neoprene Sleeve Functionality

Purpose of Test

To determine the feasibility of using L-shaped rails (a set of vinyl archway corner bead) to align and support the carriage system.

Verification Quantity

General functionality.

Pass/Fail?

Fail

Test Procedure

The L-Shaped rails were attached to the testing tube using springs to hold them in place and with the "L" shape facing away from the center. They were further reinforced using stacks of the rubber strips that had been previously used as rails. The diffraction grating mechanism was then mounted and secured onto the testing tube using clamps and a ratchet strap. The carriage was aligned so that its wheels were placed inside the rails. The carriage motor was then powered to test how much current was required to actuate it, and how well the rails worked towards keeping the carriage aligned to move in a straight line around the testing tube.

Setup

A set of two L-shaped rails was placed over the neoprene sleeve, on opposite sides of the carriage, and held together by springs.

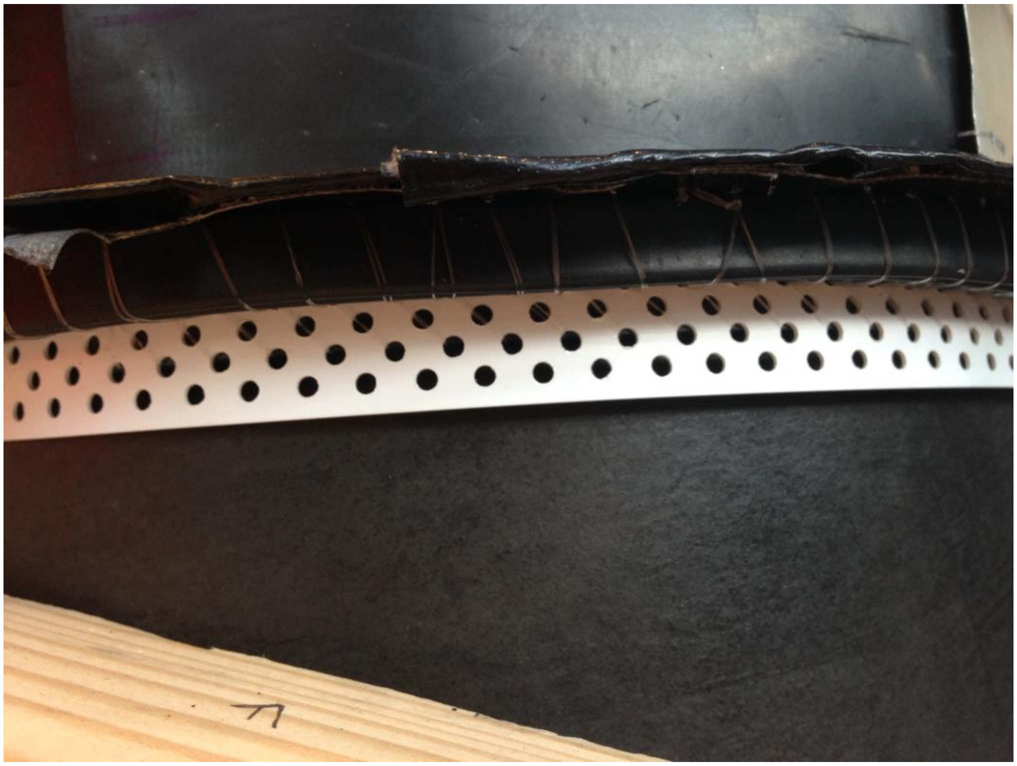


Figure 47. L-Shaped Rails

Recorded Data

(If Any)

Results

The new set of rails had higher walls, but in order for them to bend, cuts were made along the walls at equal distances. These cuts made the walls of the rails very flimsy, which did not provide any support for the carriage, and thus did not help with its alignment. In this case, the friction was not an issue since the rubber wheels were now in contact with vinyl which did not restrict its movement.

The results for this test showed an improvement in reducing the friction between the rails and the wheels of the carriage. Unfortunately, the rails were also easily bendable, so the test showed that the same set of rails could be retested if the walls were made sturdier.

Magnetic Guiding Rail + Neoprene Functionality

Purpose of Test

To determine the feasibility of using magnets as a way to guide the carriage along a steel strip.

Verification Quantity

General functionality.

Pass/Fail?

Fail

Test Procedure

The diffraction grating mechanism along with the neoprene sleeve and steel strip were attached to the testing tube using clamps. The carriage was placed over the steel strip and its motor was powered to test how well the steel strip worked for aligning the carriage.

Setup

Magnets were hot glued to a bottom plate on the carriage, and a steel strip was sewn onto the neoprene sleeve.

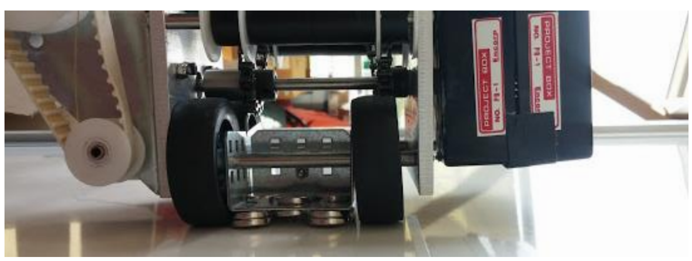


Figure 48. Magnets Testing

Recorded Data

N/A

Results

The use of magnets increased the tension between the carriage and the testing tube, which could be used as an alternative to using the ratchet strap to hold down the carriage to the tube without restricting its motion. However, the lack of side walls was a problem because the

alignment of the carriage was still being affected and the carriage was free to rotate sideways as it moved along the tube.

L-Shaped Rails + Magnetic Inner Guide + Neoprene Sleeve Functionality

Purpose of Test

To determine the feasibility of using a combination of L-shaped outer rails and magnetic inner guide rails to align and support the carriage.

Verification Quantity

General functionality.

Pass/Fail?

Pass

Test Procedure

The rails were attached to the testing tube using springs to hold them together. The entire diffraction grating system was then mounted on top of the neoprene using clamps only. The carriage was aligned on the inside of the rails, in the center matching the position of the magnets and the steel strip. The carriage motor was then powered to test how well the rails kept the carriage aligned and how much the testing tube could be moved before the carriage started to fall off.

Setup

Magnets were hot glued to a plate placed at the bottom of the carriage and a steel strip was sewn onto the neoprene sleeve. In addition, due to the short amount of time available to find materials to test, we opted for the resources that were easily available to us and used gorilla tape to make the rail walls sturdier. Also, the original rubber rails were sewn on the outside of the L-shaped rails, through the neoprene, to add more support and keep them straight.

Figure 49. Final Rail Design

Recorded Data

N/A

Results

The carriage successfully traveled in a straight line along the guide rails. The tension holding down the carriage to the tube was also sufficient to keep it attached to the testing tube. One issue we did come across was a constant clicking sound coming from the magnets and the steel strip. As the carriage rode along the rails, the magnets kept pulling on the steel strip. The steel strip was not sewn very tightly, and since the fishing line used was sewn across the steel, the magnets produced a clicking noise every time they crossed the fishing line along their path.

Using these results it was confirmed that the new rail design was greatly improved and functional. The only additional improvement required was to sew the magnetic strip in parallel lines running along the outside and the middle of the steel, but not across. This would prevent the magnets from getting stuck on the rails, making the carriage easier to move.

Ratchet Strap Functionality Test

Purpose of Test

To determine the feasibility of using a ratchet strap (typically used for tying down objects on top of your car) to hold the carriage onto the telescope, without restricting the motion of the carriage.

Verification Quantity

General functionality.

Pass/Fail?

Fail.

Test Procedure

Attach the strap and tension the strap enough so that the carriage will not fall off the tube. Assemble the drive chain system and power the carriage motor. Observe whether the system runs smoothly, if at all, and orient the testing tube at various extreme angle positions.

Setup

Run the ratchet strap around the testing tube and through the carriage. We played around with the different locations that the strap could go through the carriage at. We tried running the strap over the wheel shafts of the motor, and we tried running the strap over the rollers on top of the carriage where the chains are located.

Figure 50. Ratchet Strap Testing

Recorded Data

A zero degree incline, where the carriage was strapped to a horizontal table allowed the carriage to move.

Results

In order to hold the carriage onto the telescope, the strap had to be tensioned too high to be able to continue to run the carriage. The strap added friction between the carriage and the ratchet strap that was too large to overcome. We played around with different tension values, but could not find a happy medium.

Recommendations, Design Changes and Future Steps

We needed to find a system that would pull the telescope toward the center of the telescope without adding friction, which seemed nearly impossible. That's when we decided to test out the idea of magnets.

Scissors Subsystem

Stock Aluminum Bar Functionality

Purpose of Test

Initial testing to determine the feasibility of using the stock aluminum bars purchased from RobotShop as the main linkages in the scissor mechanism.

Verification Quantity

General functionality.

Pass/Fail?

Fail.

Test Procedure

Two full scissor mechanisms were assembled using a variety of fasteners (see individual reports *Rivet Fastener Functionality* and *Alternate Fastener and Insert Functionality* for fastener results). Data was then collected on the weight of the scissors, the force required to actuate the scissors, and the precision achievable.

Setup

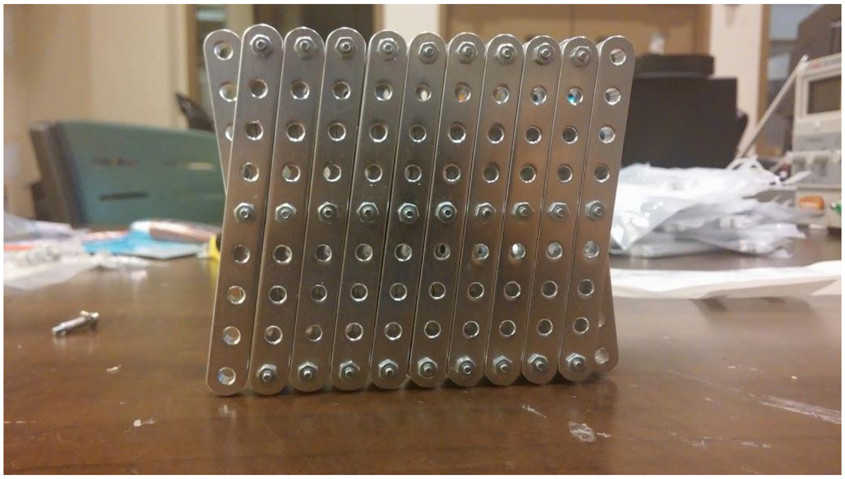


Figure 51. Aluminum Scissors Testing

Recorded Data

Fastener Used	Force Required (lbf)
Rivets	Negligible
Screws	1.1825

Results

The aluminum bars were heavy, had high friction, and came with consistent but non-standard holes. While the weight was expected and accounted for in the original design, without finding perfectly fitting (locational interference fit) fasteners, this design would be difficult to use.

Additionally, the fasteners used cannot be overly tight, due to the approximate coefficient of friction between aluminum being 1.

Due to these test results, it is recommended that further testing be done on specific fasteners.

Due to these test results, it is recommended that alternate linkages be explored.

Rivet Fastener Effectiveness

Purpose of Test

To determine the feasibility of using stock .112" rivets to fasten the aluminum scissor bars.

Verification Quantity

General Precision.

General Fiction/Force Required to Actuate.

Pass/Fail?

Fail. Not precise enough.

Test Procedure

Stock two-piece tubular rivets .112 inches in diameter (Item 96082A100 from McMaster-Carr) were the only rivets that could be found which were small enough to fit into the holes of the aluminum bars purchased from RobotShop. Other rivets were found; however, they were either too large, or had to be purchased in lots of over 1,000.

Setup

A full set of scissors was constructed from the stock aluminum bars, using the copper rivets purchased from McMaster-Carr. These were loosely pressed together so that the rivets formed a permanent bond, but did not significantly increase the frictional resistance between the aluminum bars.

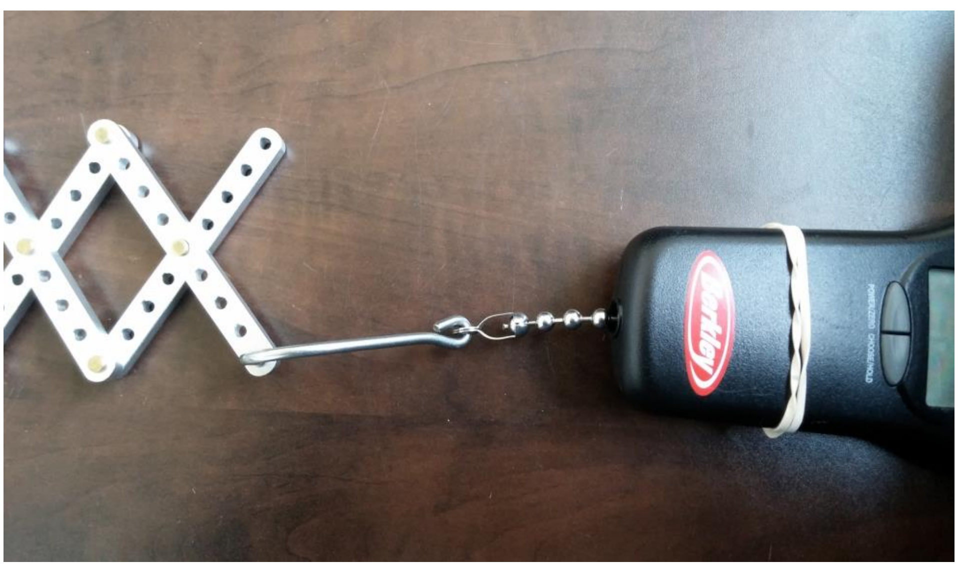


Figure 52. Aluminum Bars with Connecting Rivets Testing

Recorded Data

Force required to actuate: Negligible (less than 1 oz.)

Weight: 0.4167 lbf.

Positional backlash at each hinge: 0.019-0.020 inch.

Results

The strength and stiffness of this configuration were excellent, with the aluminum bars and rivets refusing to flex even when the scissors were fully extended into their most cantilevered position. The calculations performed that predicted this were shown to be quite accurate.

Disappointingly, the ⅛" rivets were much smaller than expected (0.112 inch instead of 0.125 inch), and the holes in the aluminum bars were much larger than expected (0.138 inch instead of a standard 0.125 inch). This allowed the aluminum bars to slide a measured 0.019-0.020 inches relative to each other at each hinge point. While this would be close to within tolerance for an individual pair of bars, each scissor mechanism contains 10 pairs of bars. Because of this, over the length of the scissor mechanism there would be up to 2 inches of slop.

Attempting to increase the pressure with which the rivets were compressed resulted initially in a slight increase in precision, at the cost of a significant increase in the force required to actuate the scissors. As the scissors were actuated repeatedly, this increased pressure would quickly lose its effect, and the scissors would return to their loose state.

We also observed an interesting "slinky effect" where one side of the scissor mechanism would expand or contract to a new size, while the opposite side would follow to a lesser degree. This lead to the period between the location of diffraction bars varying across the length of the mechanism.

Recommendations, Design Changes and Future Steps

The best way for this design to be accomplished would be to use the 0.149 inch McMaster-Carr rivets, while drilling out the aluminum bars to create a locational interference fit. However, this would require specialized bits and/or reaming equipment, as well as modifying a total of 112 holes. As this no longer constitutes a simple and easy series of operations, this was deemed to be a violation of the "off the shelf" requirement, and other methods were looked into.

Other options proposed at this point include the following:

- Alternate fasteners such as screws, inserts, pins and dowels. (Explored in *Alternate Fastener and Insert Functionality*)
- Alternate linkages such as ABS plastic (LEGOs) or wood.(Explored in *Rivet Fastener Effectiveness)*
- Modifications to the scissor mechanism, such as placing it under spring loaded tension or some form of compression. This would compensate for the slop and backlash by consistently pushing the mechanism to its minimum or maximum position.

The extreme difficulty in finding bars and fasteners that fit together with the required precision is one of the strongest reasons we recommend that this project dispense with the “off the shelf” requirement for future iterations.

Alternate Fastener and Insert Functionality

Purpose of Test

To determine the feasibility of using washers or aluminum spacers to increase the precision of the scissor mechanism.

Verification Quantity

General Precision.

General Fiction/Force Required to Actuate.

Pass/Fail?

Fail. The force required to actuate the scissors was significantly increased.

Test Procedure

These tests continue the Stock Aluminum Bar Testing and Rivet Fastener Effect line of testing.

Setup

The .112 inch rivets in the scissor mechanism were replaced with ⅛" machine screws, with thin aluminum washers at each end. These machine screws were then finger tightened until the washers deformed slightly. This slight deformation was designed to keep the holes within the aluminum bars concentric with each other.

Inserts were not attempted, as after extensive searching no off the shelf part could be found that would fit correctly.

Figure 53. Scissors with Connecting Alternate Fastener and Insert Testing

Recorded Data

Force required to actuate: 1.1825 lbf. Avg, peaking at 2.125 lbf.

Weight: 0.5625 lbf.

Positional backlash at each pin: 0.001-0.003 inch.

Results

This method proved extremely effective at maintaining the precision of the individual hinges within the scissor mechanism. However, it significantly increased the force required to actuate the scissors, without eliminating the scissor effect that accumulated across the length of the scissors, with a cumulative backlash of up to 0.250 inch being found.

The prevalence of the slinky effect while using this method was appears to be a result of the high friction between the aluminum bars. This friction effectively causes the bars that are not directly actuated to drag behind, those that are, causing the slinky effect.

Recommendations, Design Changes and Future Steps

Because this method significantly increases the hardware, weight and friction within these parts, without fully eliminating our precision problem, this method is not recommended for use.

These experiments make it clear that a very carefully designed and fitted hinge is required, which may not be at all possible with off the shelf parts.

Abs (Lego) Scissor Functionality

Purpose of Test

To determine the feasibility of using Lego Technic bars in place of aluminum bars.

Verification Quantity

General functionality.

Stiffness: Overall deflection less than 0.020 inch when horizontal.

Precision: Locational Tolerance of ±0.020 inch for each bar relative to the ones next to it.

Force to Actuate: 0.10 lbf preferred maximum. As low as possible otherwise.

Pass/Fail?

Stiffness: Fail.

All others: Pass.

Test Procedure

The Lego scissors were constructed similar to the previous aluminum ones, with Lego technic bars approximately 3 inches long being used instead of aluminum bars. Black Lego Technic friction pins were used as the hinges instead of rivets or screws.

Setup

The Lego scissors were tested in the same way as the aluminum scissors. A force meter was attached to the bottom holes to simulate the way in which the scissors would be actuated, and the maximum forces required to move the scissors recorded.

Figure 54. LEGO Scissor Testing

There was no measurable backlash at the individual hinges. When actuated with no resistive force, the scissors as a whole had very little locational variance, typically falling within 0.100 inch, and often being impossible to measure. When a resistive force was added however, it was extremely easy to flex the scissors in either direction.

This flexibility continued to be a problem when we tested the overall stiffness of the scissor mechanism. When extended to its full length, the Lego scissor mechanism would flex up to 1 inch with no load.

Recorded Data

Force Required to Actuate: ~0.0625 lbf.

Weight: 0.040 lbf

Flex: 4 inch droop.

Results

Using the Lego Technic pieces we were able to attain an incredibly high level of precision. If this project were to continue to use off the shelf parts, it would be incredibly difficult to achieve a higher level of precision.

In addition to this, the Lego scissor mechanism was much more lightweight than the aluminum version.

The force required to actuate the Lego scissor mechanism was higher than that required to actuate the rivet fastened Aluminum scissors, but were still extremely low.

The only area that the Lego scissors failed in was stiffness.

Recommendations, Design Changes and Future Steps

Our original calculations predicted that we would need the aluminum scissors, due to the ABS plastic not being stiff enough. This was proven to be the case, though more due to the flexibility in the pins used to connect the Lego Technic bars than the bars themselves. However, since the Lego scissors passed all other requirements with flying colors, we would strongly recommend using these parts, and finding an alternate solution to the stiffness problem.

Carriage Full Range Limits

Purpose of Test

To determine the full range of motion of the scissors system.

Verification Quantity

General full range of motion

Pass/Fail?

Pass

Test Procedure

We powered the scissors mechanism to its maxed out position and to its minimum position and measured the distance between the bars as well as the full width of the grating.

Setup

Figure 55. Scissors Full Range of Motion

Recorded Data

The maximum full width of the grating was 28.25 inches with the width between the grating being 1.5 inches. The minimum full width of the grating was 20 inches with the width between gratings being 0.75 inches.

Results

The system achieved a ratio of 2:1 for the spacing between gratings.

Recommendations, Design Changes and Future Steps

We don’t recommend using the grating at its maximum or minimum widths because they are the extreme values and can cause stress on the motor or it could damage other features of the system.

Support Frame Subsystem

Dual Shaft Motor Functionality Test

Purpose of Test

To determine the feasibility of using a dual shaft motor to drive the power screws in order to actuate the scissors.

Verification Quantity

General functionality.

Pass/Fail?

Fail.

Test Procedure

Assemble the system and power the motor. Continue to increase the current until the screws begin to rotate smoothly or you reach an upper limit of 5 amps. Reverse the polarity of the motor several times and ensure that the system can rotate smoothly in both directions.

Setup

Assemble the dual shaft motor with its highest gear ratio of 131:1, then thread each end of the motor shaft into both drive screws. Attach the scissors to the drive nuts and thread the nuts onto the drive screws. Connect power leads to the motor.

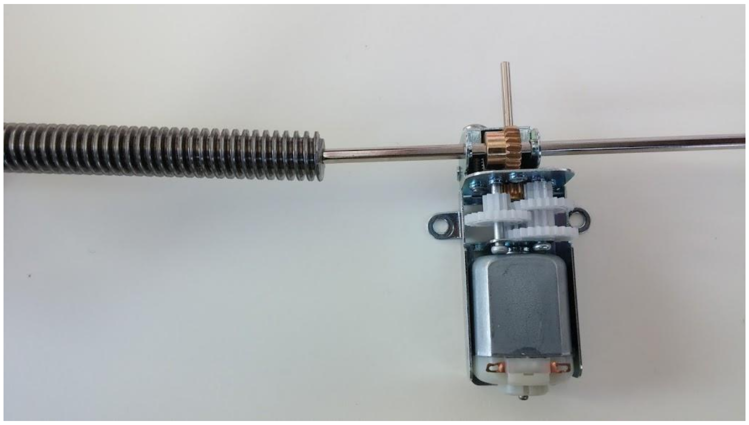


Figure 56. Dual Shaft Motor

Recorded Data

The motor required a current higher than 5 amps to actuate. We did not determine the exact current because we didn't want to burnout the motor.

Results

The motor was powerful enough to rotate the two lead screws without any load on them. However, as soon as we attached the drive bearings (even without the weight of the scissors attached), the motor could no longer rotate the drive screws.

Also, as we rotated in each direction, the motor shaft would unscrew itself out of the drive screws.

Recommendations, Design Changes and Future Steps

This is the only dual shaft motor we could find that is small enough to fit on our system, so we decided to redesign how we power the lead screws. We decided to use a single shaft motor that can emit a larger torque, and a combination of gears to transfer the torque to the shaft.

In order to keep the drive screws from unscrewing off of the motor shaft, we added Loctite to keep it in place.

Gear Train Motor Functionality Test

Purpose of Test
To determine the feasibility of using a gear train to transfer the motor torque to the drive screws.

Verification Quantity
General functionality. Minimal backlash. No slippage.

Pass/Fail?
Pass.

Test Procedure

Initially we tried to use bevel gears to transfer the torque to the drive screws by putting one bevel gear on the motor shaft and the other on the double threaded shaft connecting the two drive screws. The motor would be oriented perpendicular to the connecting shaft and the torque would be transmitted at a 90 degree angle. However we need two different bore diameters (3mm and 4mm) but the same pitch. We could not find any bevel gears that exactly matched our desired dimensions so we ordered 2 4mm bore bevel gears with a pitch of 20. Unfortunately, the clearance between the 3mm shaft and gear bore was too large to transmit any torque, and the pressure angle was wrong so it couldn't transmit torque a full 90 degrees, but about 45 degrees. This design was not adequate so we decided to try a pair of spur gears.

We ordered two spur gears and attached one to the connecting rod and one to the motor shaft. After perfecting the distance between the two gears so that they stay in contact with each other at all times, we ran the motor several times in both directions with the drive bearings attached and the scissors mounted to the bearings and ensured smooth continuous motion.

Once we knew the system was powerful enough to move the scissors, we hooked up the motor with the current turned off and then continued to raise the current until the scissors began to move to determine what power to run the motor at.

Setup

We mounted the motor parallel to the bar and attached power leads to the motor.

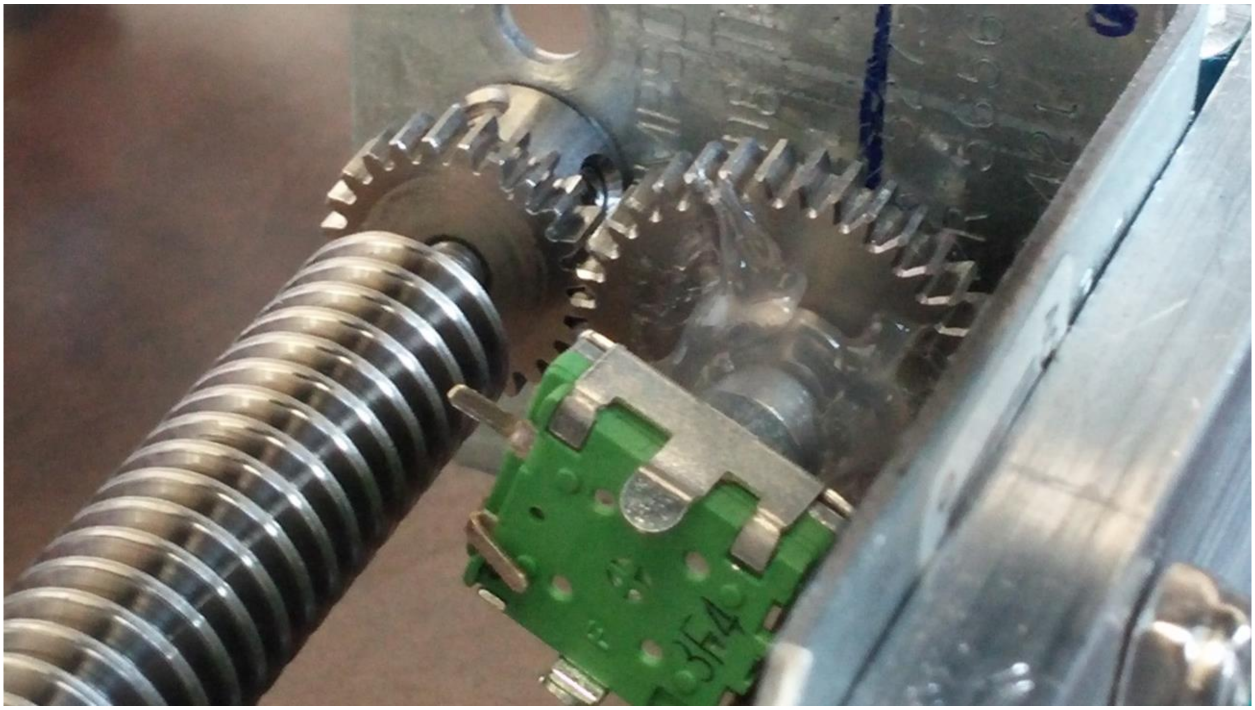


Figure 57. Gear Train

Recorded Data

The motor ran adequately at 0.2 amps.

Results

The spur gear train proved powerful and reliable enough to actuate the scissors mechanism. The gear ratio between the spur gears results in very small intervals of movement in the drive shaft. This is desirable because it results in precise positioning of the scissors and will be easier for the encoder to keep track of the position of the scissors.

Recommendations, Design Changes and Future Steps

The system runs properly and successfully with the spur gear train. The screw attaching the motor to the motor bracket keeps the motor from resting flush on the motor support, so the motor is slightly tilted. This geometry restricts the placement of the motor mount because if it is perfectly parallel with the drive screw, the motor runs into the screws. It is important that the motor is parallel with the screws so that the gears mesh properly, so we recommend mounting the motor support slightly crooked with a 1 degree angle.

Software

Software Implementation and Testing

Purpose of Test

To confirm that the software has been correctly implemented, and to test the functionality of the drivers and the software communication system.

Verification Quantity

100% Driver Functionality.
100% Command Functionality.

Pass/Fail?

Pass.

Test Procedure

These tests were conducted in conjunction with the testing of the electrical systems.

Initially, the motor driver and encoder library were tested individually by uploading to the Arduino, and monitoring the output signals generated by each.

Once the individual drivers were tested, they were combined into one package, and tested together on first the breadboard setup, and then the electrical system integrated into the actual Automatic Diffraction Grating. These tests consisted simply of outputting signals to the motors and observing the response, as well as observing the encoder response from the driven shafts.

Once the functionality of each of the drivers in conjunction with each of the electrical components was confirmed, we proceeded to test each of the remote control commands by sending instructions from a laptop over USB. Individual commands were written for control of the scissors, the carriage, and for toggling between automatic and manual mode. Each of these was tested in turn and for a variety of potential inputs including:

- Range of values.
- Minus signs.
- Mistyped commands.
- Multiple commands in rapid succession.
- EBCAK (error between chair and keyboard) errors.

Setup

See setup in Electrical Implementation and Functionality Testing.

A screenshot of the startup screen is included below.

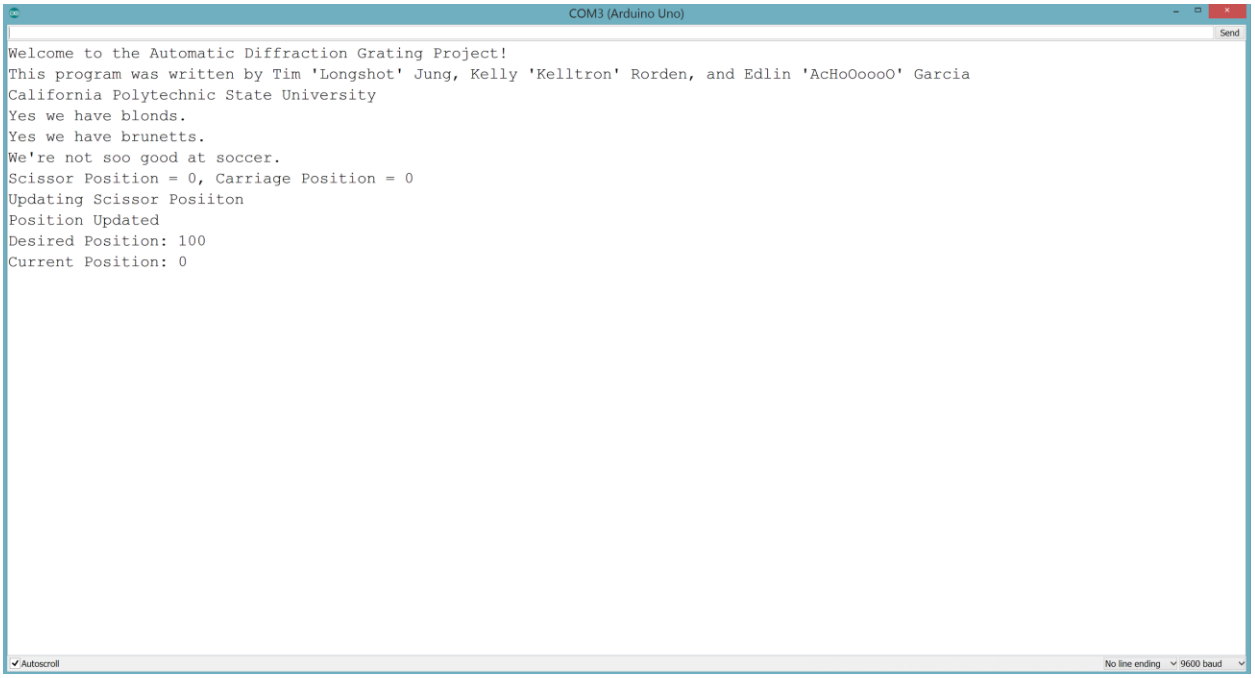


Figure 58. Screenshot of Startup Screen

Recorded Data

N/A

Results

With the exception of the USB/Motor 3 conflict (discussed in Electrical Implementation and Testing), each of the commands functioned as expected. While this is not the full and direct control of the Automatic Diffraction Grating by typical astronomy software, this demonstrates that the system can easily be controlled remotely. Furthermore, the commands are simple and use standard ASCII enumeration, meaning that any program able to output simple characters over USB would be capable of communicating with this software.

Recommendations, Design Changes and Future Steps

If, as recommended by the results of the Electrical Implementation and Testing, the Arduino Uno is swapped out for an Arduino Mega, it will be necessary to modify the pin numbers to match the new inputs and outputs.

Electrical Components

Electrical Testing and Implementation

Purpose of Test

To confirm that the electrical systems were properly integrated into the Automatic Diffraction Grating, and are fully functional.

Verification Quantity

100% Control and Functionality.

Pass/Fail?

Conditional Pass. Motor driver 3 will not function during USB communication.

Test Procedure

The majority of the initial testing for the electrical systems of the Automatic Diffraction Grating were conducted during the assembly of those systems.

Before integration was begun, the two motor drivers and the two encoders were mounted to a breadboard. This allowed the Arduino Uno to be connected, and used to drive an individual motor. Once this had been accomplished, a stripped down version of the final code which included the motor driver class and the encoder library, was uploaded to the Arduino. Using this, we were able to confirm that the proper signals were being sent to each of the motor drivers, and that the Arduino was able to read both of the encoders.

Once we had shown that we could control each of the required components, the motor drivers and encoders were dismounted from the breadboard and mounted to the carriage subsystem, and re-tested with the Arduino, again using the basic test program. Once the functionality of each component was confirmed, we continued this testing with the full software installed.

Due to the cost of the electrical components, we did not purchase backups for each individual component. Therefore we decided not to conduct tests into the full current and power capacity of the electrical components.

Setup

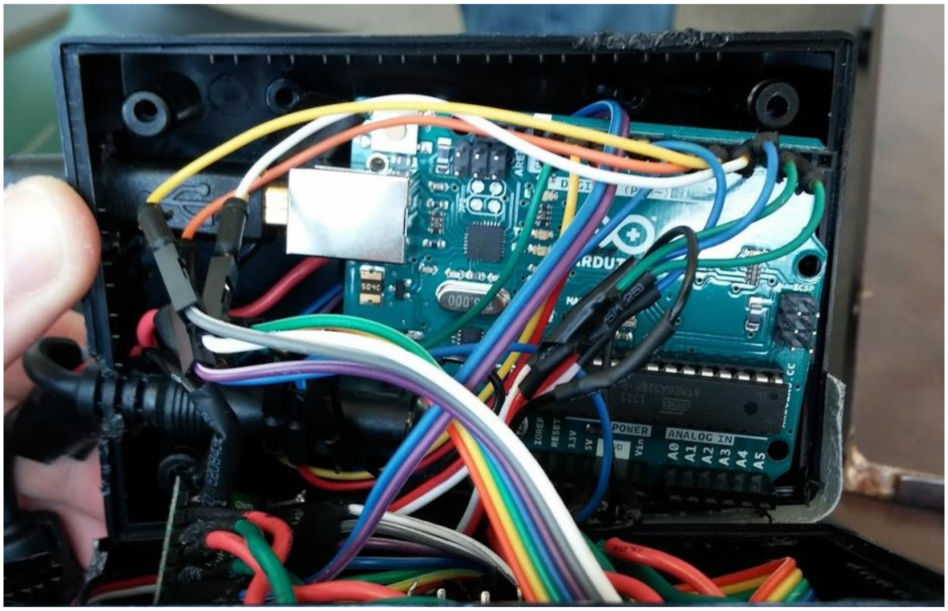


Figure 59. Electronics

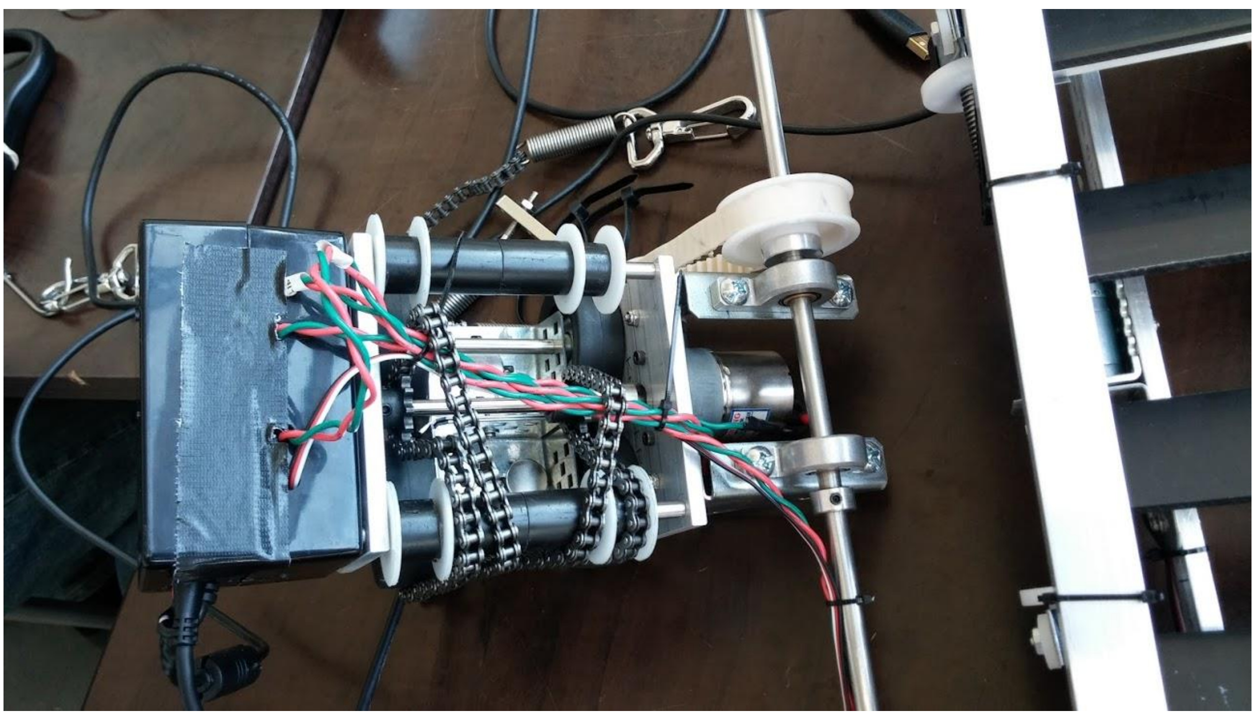


Figure 60. Electronic Connections

Recorded Data

N/A

Results

The Arduino and associated hardware proved more than capable of running the motor driver chips.

While the Arduino Uno only has two interrupt pins, it was able to read the inputs from both quadrature encoders, rotated in both directions, without apparent miscounts or loss of data. This is primarily due to the slow rate at which the encoders are rotated, the extremely efficient interrupt service routine (ISR), and the minimal design of the co-operative multitasking process.

One major issue that did arise was the discovery that the Arduino Uno cannot properly control Motor 3 (the flip up mechanism) while communicating with a laptop over USB. This is due to the fact that serial communications are shared with pins 0 and 1 on the Arduino Uno, causing any signals being sent to the motor on these pins to fluctuate whenever serial data is transmitted. Without this issue, the Arduino Uno has the exact number of pins required to run the full Automatic Diffraction Grating system. With these pins removed, the Arduino would not be able to control everything required, without modification to either the Arduino, or the motor driver chips.

Recommendations, Design Changes and Future Steps

In order to achieve full control over USB, while maintaining full functionality of the Automatic Diffraction Grating, it is necessary to upgrade from an Arduino Uno to a larger board such as an Arduino Mega. This will require minimal modification of the software written for this project, but will require a redesign of the electrical component housing.

Specification Verification Checklist

See Appendix G (DVPR).

The DVPR table in Appendix G shows the testing procedures we plan on doing in order to verify that our design works. The number in the specification or clause reference column refers to the design requirement that we are testing. The next column explains how the test will work and the following column specifies the passing requirement. From there the table specifies which member of our team is responsible for ensuring that the test gets done and that all measurements are accounted for. This table will be used as a guideline when verifying the quality of our design.

Chapter 7: Design Modifications

Introduction

Over course of this project, the design of the Automatic Diffraction Grating changed significantly due to discovered design flaws, availability of components, complexity, and upgrades. However, the overall design remains essentially the same, and the final product is immediately recognizable as what was modeled for the critical design report.

Among the most noticeable of the design changes were the switch from Aluminum to Lego Bars for constructing the scissor mechanism, and the replacement of the strap down system with magnets. Below is a detailed description of the modifications to our overall design.

Carriage Subsystem

The overall functionality of the carriage has remained the same, we have only added features and adjusted the assembly. Below are features of the carriage design that have been modified.

Carriage Top Plate

The top plate used to mount the bearings that attach the support frame to the carriage has been removed from the design. This plate initially rested on the triangle brackets because the holes on the bracket did not match up with where bearings needed to be mounted. Due to modifications in the support frame, we had to adjust the position of the bearings. This allowed the bearings to be mounted to the already existing holes in the triangle brackets and removed the need for the top plate.

Magnet Feature

Initially we thought that the tension in the chains themselves would be sufficient to hold the carriage to the telescope itself. However, as you can read in Chapter 6, we went through several iterations and the solution that produced the best results was the use of magnets. We used 20 magnets in total that are attached to two brackets at the bottom of the carriage. The brackets were slid onto the wheel shafts and butted up next to each other and bolted together.

The magnets were spread out evenly and stacked until just barely above the surface. This array of magnets is all that is needed to provide the downforce keeping the carriage on the telescope.

Figure 61. Carriage Magnets

Flip Up Subsystem

While perhaps the simplest of the subsystems in the Automatic Diffraction Grating, the flip up subsystem underwent some small but important changes.

First, the flip up mechanism was originally attached to a large aluminum mounting plate, which was bolted to the carriage. This aluminum plate was removed entirely as discussed in the carriage subsystem section, and the flip up mechanism was bolted directly to the triangle brackets on the front of the carriage.

The second modification was necessary due to the mismatch between the pulley attached to the flip up with a bore of 3/16" (4.8 mm), and the shaft that drives it (4 mm). In order for these components to be compatible, a 3/16" copper tube was purchased and inserted as a standoff between the motor and the pulley. This method was selected because a shaft coupler of the proper dimensions could not be found off the shelf, and custom parts are not within the scope of this project.

Scissors Subsystem

Of all the subsystems within the Automatic Diffraction Grating, the scissor mechanism underwent the most redesign and modification, ranging from fine tuning to complete replacement of key parts.

Replacement of Aluminum Linkages with ABS plastic (Legos)

During the initial design phase of this project, it was extremely difficult to locate an acceptable linkage for constructing the scissors mechanism. This was primarily due to the specific size and shape required, as well as the necessary precision of the part. The components eventually found from RobotShop were the closest things we could find to being the exact component we needed. However, these stock aluminum bars were drilled with a hole pattern with non-standard sizes, making it impossible to find stock fasteners that could hold the bars together, while providing a hinge point, and without significantly increasing the weight of the mechanism.

At this point, the options remaining were to modify each of the holes on the stock aluminum bars as needed (a total of 112 holes), or finding another component to use in its place. Modifying the bars themselves was something we were hesitant to do, as not only would this require a significant amount of machining on our part, it would significantly increase the amount of effort required from an astronomer or do-it-yourselfer.

Replacing the aluminum bars also looked to be an extremely difficult task. Significant amounts of time had already been spent searching during the design phase, and as it became more and more apparent that the aluminum bars were not going to work, a large amount of time was spent searching for an alternative. Finally, as no alternative could be found for the aluminum bars, we began to examine the possibility of using alternate materials, or even an alternate mechanism. One potential solution that became immediately apparent was that we could use the same components that we had used to prototype the scissor mechanism; namely, the Lego Technic linkages. These linkages are strong, lightweight, cheap, off the shelf, and - most importantly - extremely precise: Lego bricks are known to have a tolerance of as little as 10 micrometers (0.00039 inch).

The major downside to using Legos, was that the stiffness of the Lego Technic linkages was unknown, but estimated to be very low. While this issue is a significant one, it is much easier to solve using off the shelf parts than the issue of precision or mismatching holes. This was accomplished by adding two thin aluminum bars 12 inches in length, which effectively sandwiched the Lego scissors. These bars were loosely attached so that the scissors could easily slide in or out, but were stiff enough to keep the scissors and diffraction grating straight across the width of the telescope.

Summary

In summary, the final design changes to implement the new Lego scissors are as follows:

- The stock 3 inch Aluminum Bars were replaced with 11 hole Lego Technic linkages.
- Stock Lego Technic friction pins were used in place of traditional fasteners.
- The scissor mechanism was reinforced with Aluminum Bars.

While somewhat unorthodox, replacing the aluminum bars with Lego ones significantly improved our design, maintaining our requirement for off the shelf parts. This is also one of the few off the shelf options available.

Support Frame Subsystem

The overall size and layout of the support frame basically stayed the same. The only piece we played around with is how the motor was mounted to the frame and the motor itself.

Actuating Motor

Initially the motor used to actuate the drive screws was a dual shaft motor that outputted 50 oz.-in of torque. The motor ended up not being powerful enough to rotate the drive screws with the added weight and friction from the scissors. We could not find a dual shaft motor with enough power to actuate the system but small enough to mount to our support frame. So we decided to use a single shaft motor that an exert 300 oz.-in torque with a gear train. After testing different types of motor configurations our final design consisted of two spur gears with a ratio of 2:3. The smaller gear is attached to the drive screw connector, and the larger gear is attached to the motor shaft. The motor support bar is in the same location as previously, but it is important to ensure that the motor is parallel with the drive screws so that the gears work properly.

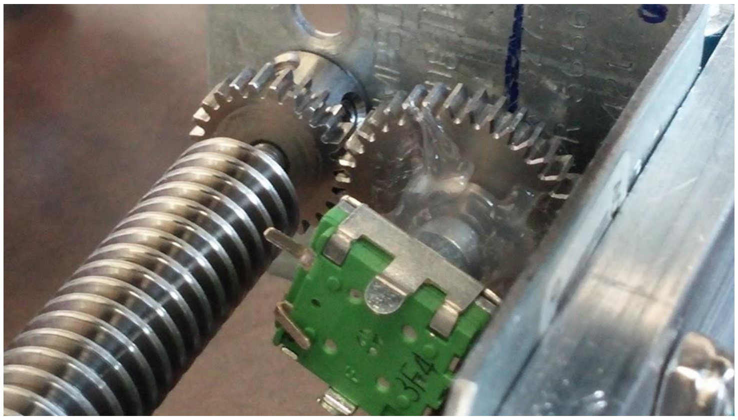


Figure 62. Gear Train

Sleeve and Rail Subsystem

The concept of a neoprene sleeve and rubber rails are still in our final design, they have just changed form.

Rails

The use of rubber strips were not rigid enough to supply any form of support for the carriage. The new design consists of using an arched drywall corner with gorilla tape as reinforcement on the frayed tips as the rails themselves. Then layering 3 strips of the rubber strips as added support on the outside of the arched corner. These were all sewn into the edge of the neoprene fabric.

Metal Strip

As mentioned in the carriage design modification section, the carriage is not being held onto the telescope using magnets. In order to give the magnets something to be attracted to, we sewed in a strip of steel in the middle of the neoprene sleeve. Holes were punched on either side of the metal and down the middle so that it could be easily sewn onto the neoprene.

Chapter 8: Conclusions & Recommendations

The Automatic Diffraction Grating project was initially intended to be a simple, repeatable, off the shelf project. As the project progressed, it became apparent that in order to meet all of the customer requirements, an involved and complex system would need to be created. Since the basic functionality of this system requires a very high level of control and precision, the overall difficulty and cost of this system increased extremely quickly.

Nevertheless, this project has served as an excellent exploration of what would be required to build a system that fulfills each of the customer requirements, how that system might be designed, and what the difficulties of implementing such a system would be. These results, findings, and conclusions are summarized within this chapter.

Conclusion of Current Project

StarT.E.K researched, developed, designed, and produced one Semi-Automatic Diffraction Grating system prototype. The purpose of this design was to measure the position angle and spacing between the two binary stars. The prototype was modeled and designed for Dr. Russ Genet's Celestron C-11 telescope with the ability of being simply modified to accommodate various sized telescopes for future use.

The Semi-Automatic Diffraction Grating system was designed for the customer requirements specified by Dr. John Ridgely and Dr. Genet, as well as the engineering specifications listed in this document and in the project proposal, however all of the requirements were not met. We were able to achieve the functional motions described in our design, but the full range of motion and the precision were not achieved. After fully assembling the sleeve with the rails and the metal plate, we could not get the carriage to move. This is due to the metal plate being pulled up by the magnets and coming into direct contact with the magnets. This increases the friction and keeps the carriage from moving. The scissors were able to reach a distance between 0.75 inches to 1.5 inches with an accuracy of $\pm$ 0.1 inches, however we do not suggest extending the scissors farther than 1.25 inches apart so that it is not too difficult on the motor to retract it from its maximum state. The flip up was able to achieve a full 90 degrees of motion to go from being in front of the telescope lens to completely out of the view of the telescope.

The selected design of team StarT.E.K for the Adjustable Diffraction Grating was a simple scissor-mechanism to actuate the bars and slots, evenly, and with a single actuator. Selected for

the mounting and rotation systems was a set of magnets that secure the grating to the telescope, and a chain and belt system that drives the carriage around the telescope.

This prototype had a target unit cost of $400, in addition to additional costs for prototyping and materials. However, because we needed a high level of precision and one of our customer requirements is to use off the shelf parts, it was very difficult to keep our price down. We have three axis of motion that involve intricate parts also increased the cost of manufacturing. The manufacturing cost for a single prototype was $907.85, and a total of $1,338.03 was used for testing and prototyping. If individuals desire to replicate our design and keep the cost down, they can machine several of their own parts, but they might sacrifice some precision.

The Semi-Automatic Diffraction grating project was completed in June 2015, and 1-2 papers will be published by team StarT.E.K. with the support of Dr. Genet.

Future Recommendations

If you are interested in building this design yourself, follow our manufacturing process and cost analysis in the appendices. Precision is a key part to ensuring good results when operating the automatic diffraction grating, so be sure to be very accurate when drilling holes and assembling the device. If you have the funds, we recommend that you outsource all of the machining to manufacturing companies such as Misumi in order to ensure precision in parts.

Because the biggest issue is the carriage becoming in direction contact with the metal strip, we suggest adjusting the orientation of the magnets and amount of magnets on the carriage until the optimum quantity is reached. We also suggest fastening the metal strip down tighter so that it doesn't have the capabilities of lifting up from the neoprene at all.

It would also be worth examining the brackets that the magnets are attached to, in order to adjust the height at which the magnets rest.

Recommendations Regarding Project Scope and Approach

Several of the findings over the course of this project, as well as the expense and complexity of the project itself lead us to the conclusion that it would prudent to make several recommendations with regards to the scope of the project.

Recommendation 1: Consider a non-DIY approach

Due to the high level of precision required for this project, it extremely difficult to find off the shelf parts that are of sufficient quality. In fact, the majority of the design and manufacture portions of this project was spent searching in vain for these sorts of components. It is also difficult to achieve the necessary precision while using hand tools and non-specialized equipment. Because of this, it may be worth designing this project to be outsourced to a machine shop, or to be easily reproduced by students at a university's fabrication facilities. At the very least, achieving the required precision will almost certainly require custom machined parts, and it is very strongly recommended that this be allowed into the scope of the project.

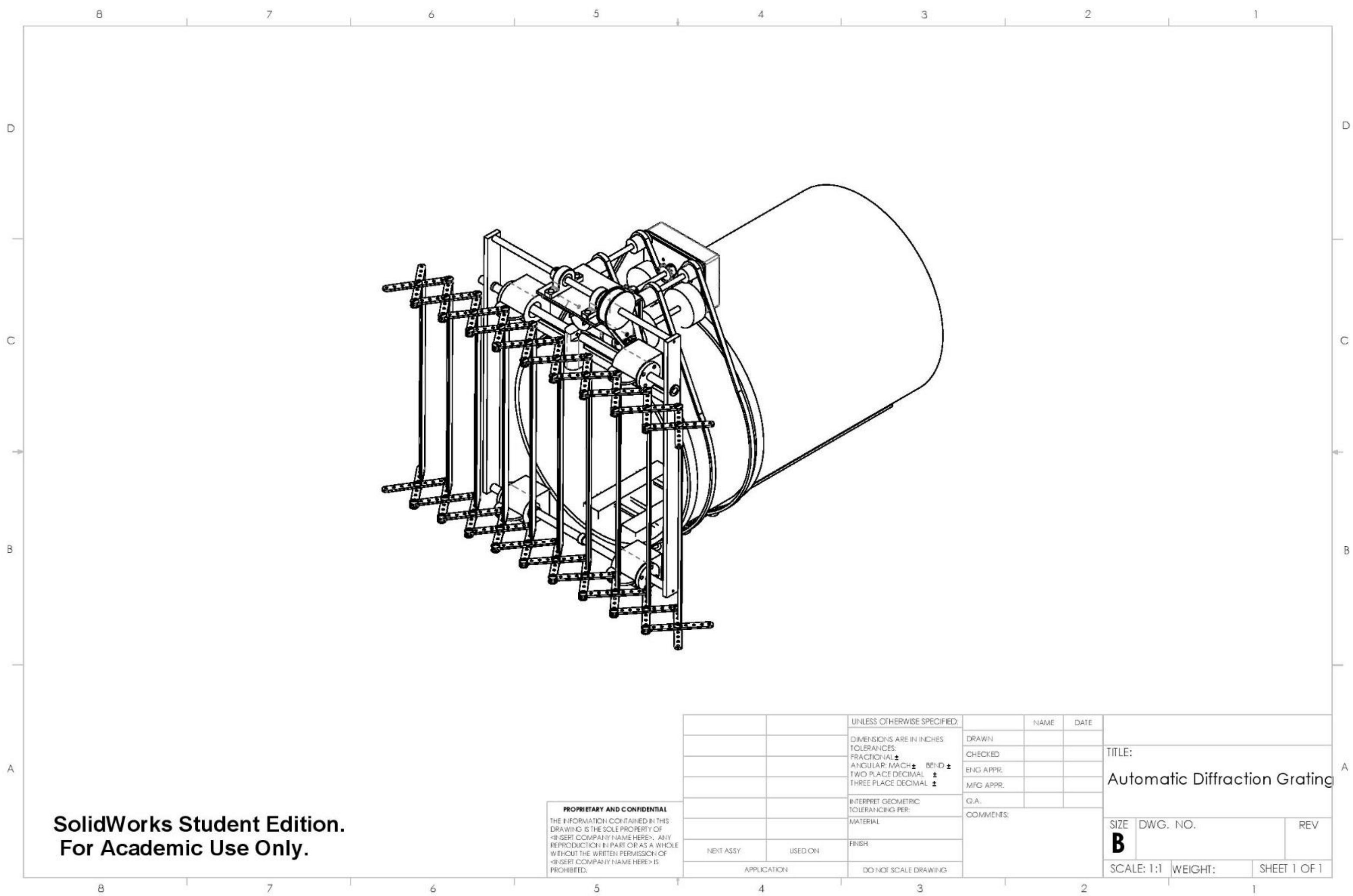
Recommendation 2: Consider non-adjustable gratings

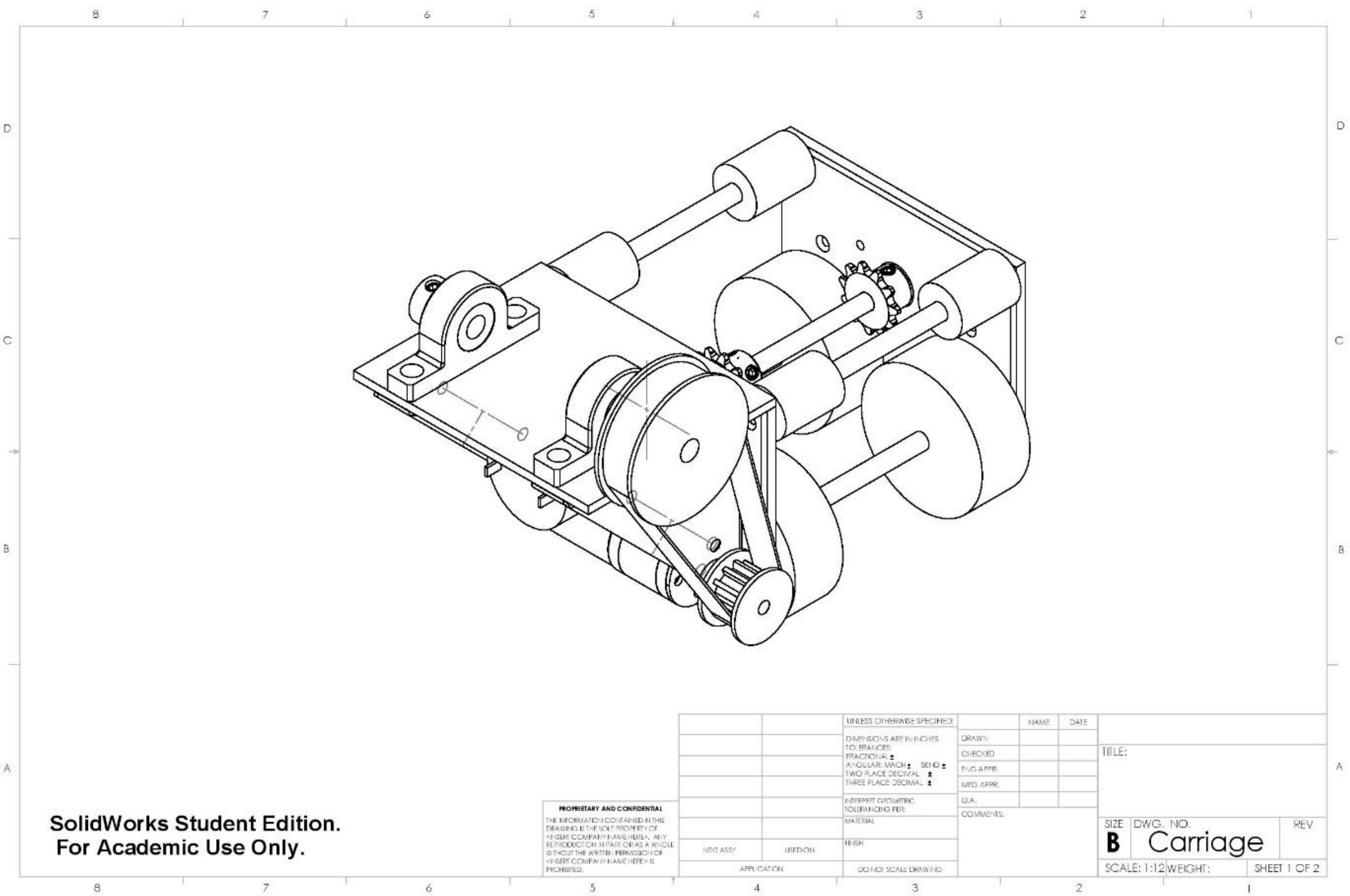
While the main goal of this project was to design and build an *Adjustable* Diffraction Grating that would be compatible with a wide range of stars, a cost analysis of this approach vs. a set of small, easily exchangeable gratings may reveal that the latter would be more cost efficient. If this is the case, it would be up to the customer to decide if the automatic adjustability is worth the extra cost, or if the automatic functionality could be accomplished some other way.

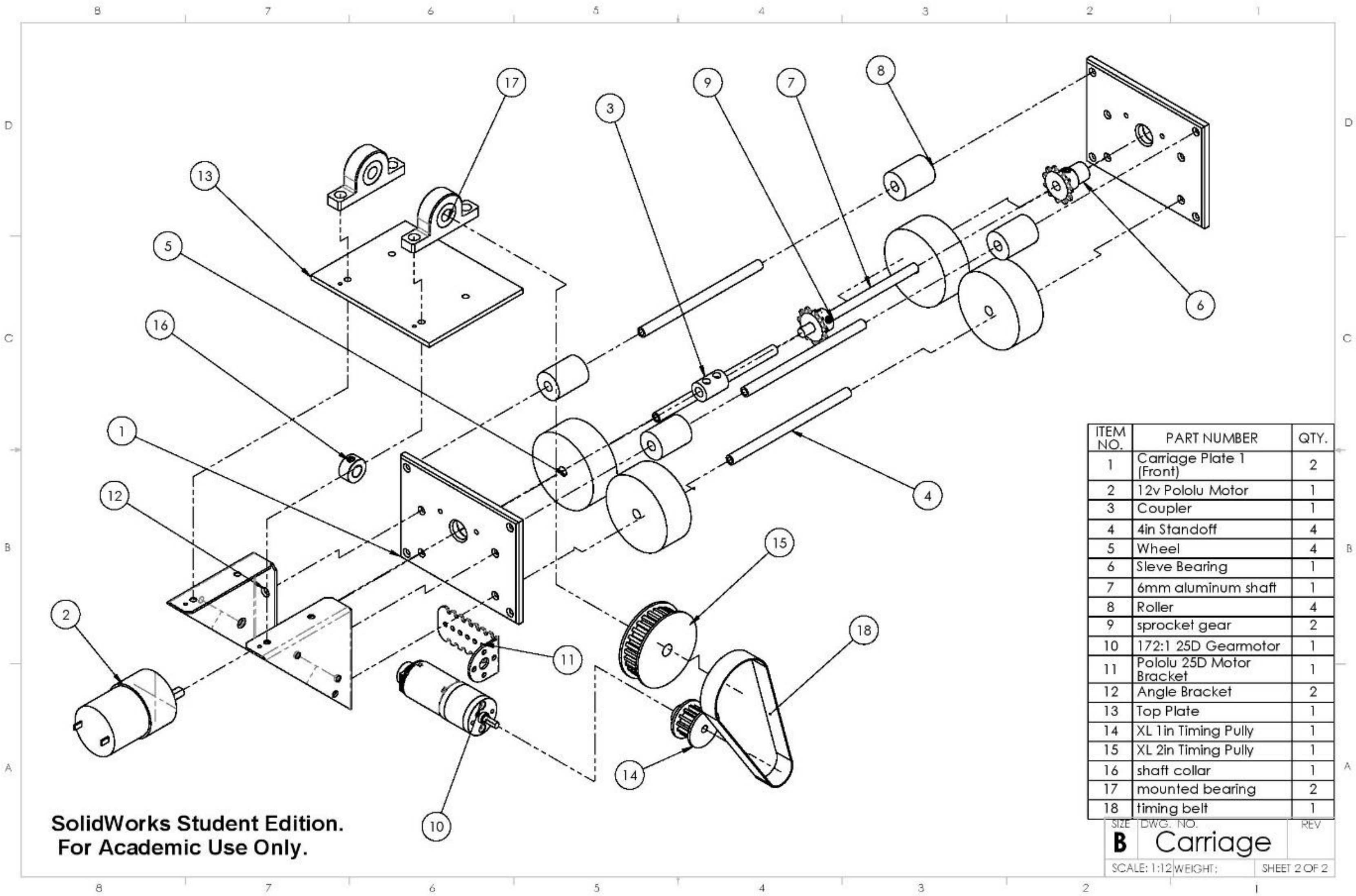
Recommendation 3: Select a Universal Mounting Option for Telescopes

As mountability to multiple telescopes is still a desired capability of this project, it is recommended that in addition to creating an easily scalable design (this project's design was intended to be easy to scale as well as capable of fitting a range of telescopes as is), a standard method for mounting to the target telescopes be found. For instance, an attachment that could clamp to a wide variety of the mounting rails commonly found on telescopes, or an adapter plate that would allow the Automatic Diffraction Grating to be bolted directly onto one of these.

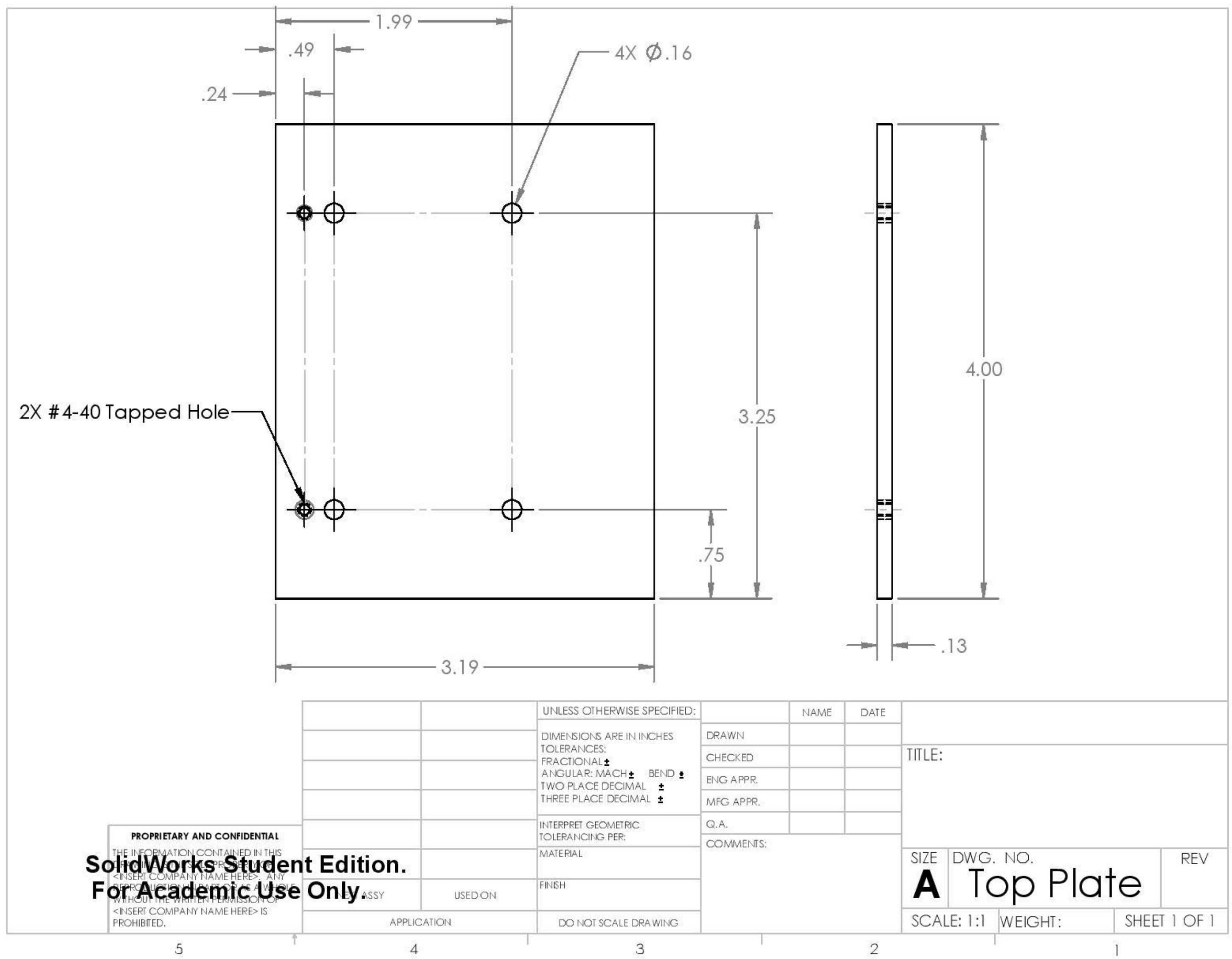
Appendix A:
Manufacturing Drawings

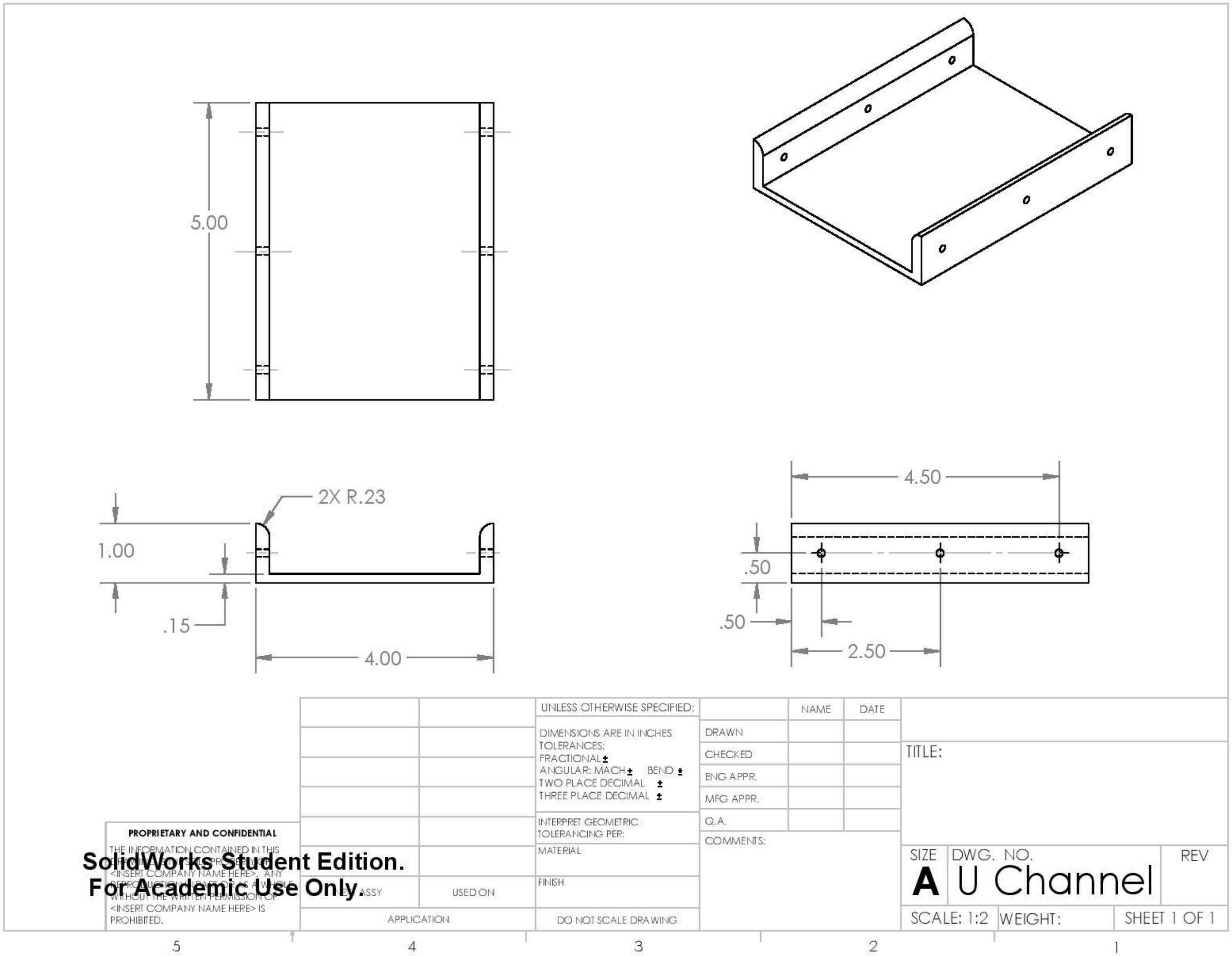

SolidWorks Student Edition.
For Academic Use Only.
PROPRIETARY AND CONFIDENTIAL
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
TITLE:
Automatic Diffraction Grating
SIZE
B
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

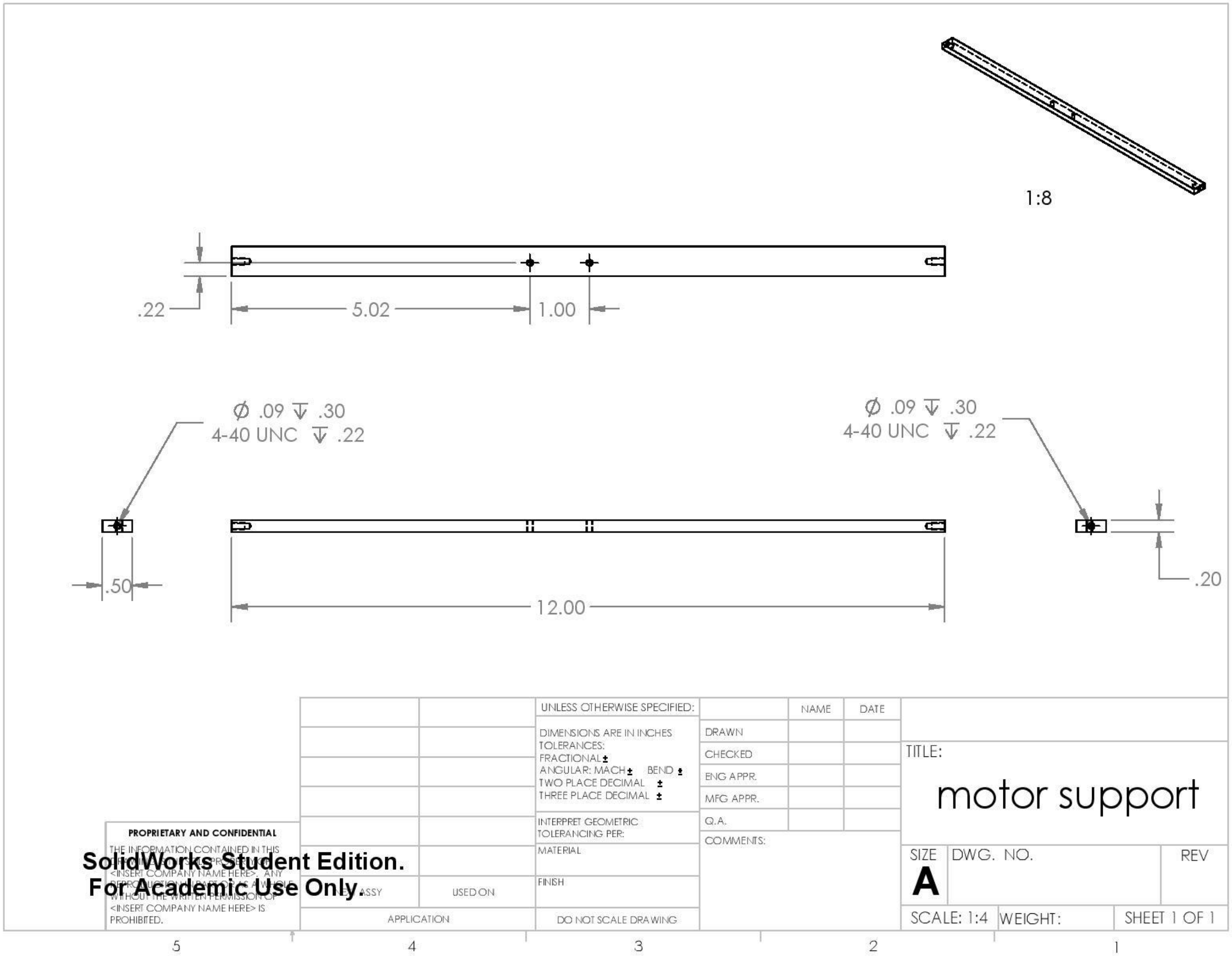

SolidWorks Student Edition.
For Academic Use Only.
PROPRIETARY AND CONFIDENTIAL
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
SIZE
B
DWG. NO.
Carriage
REV
SCALE: 1:12
WEIGHT:
SHEET 1 OF 2

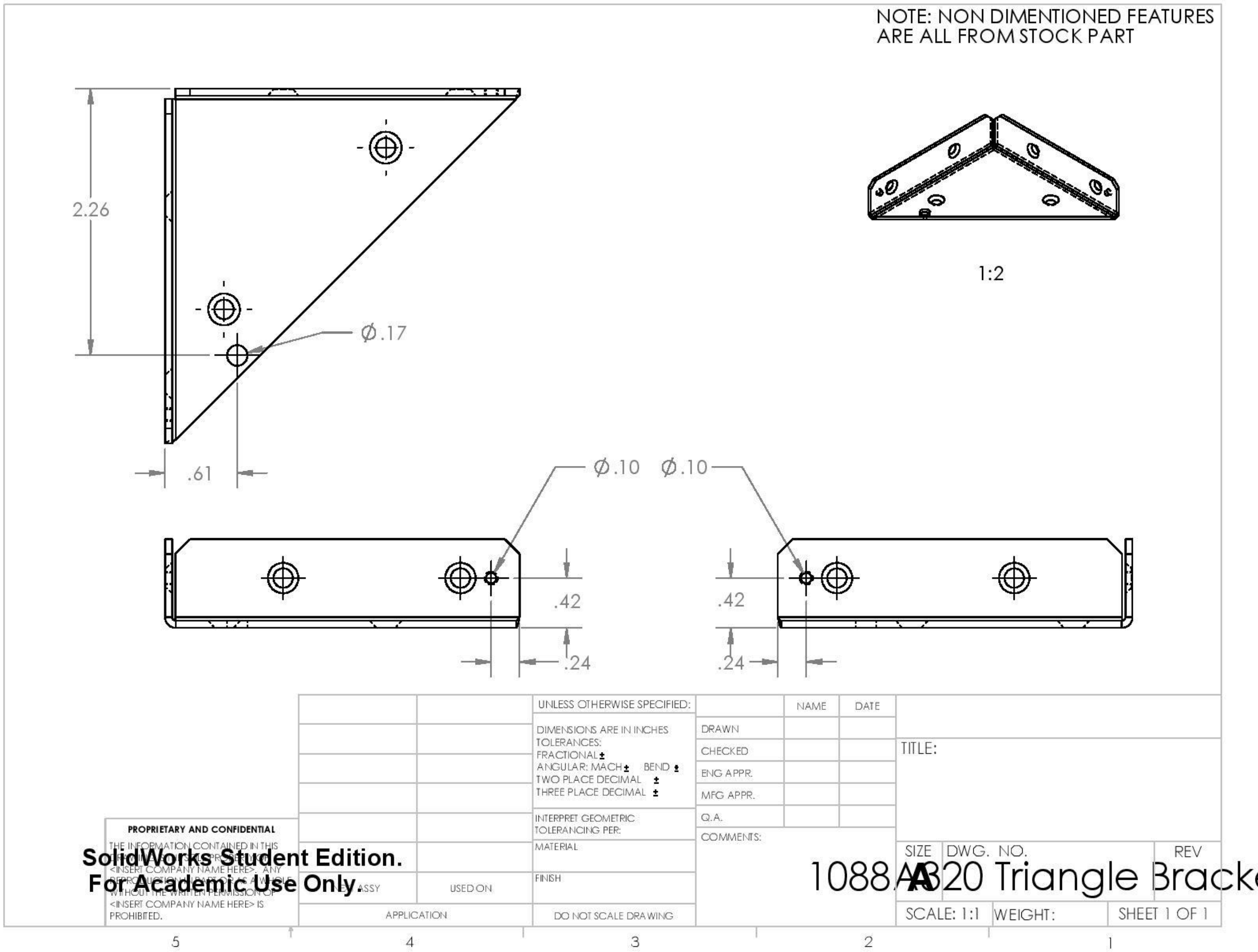


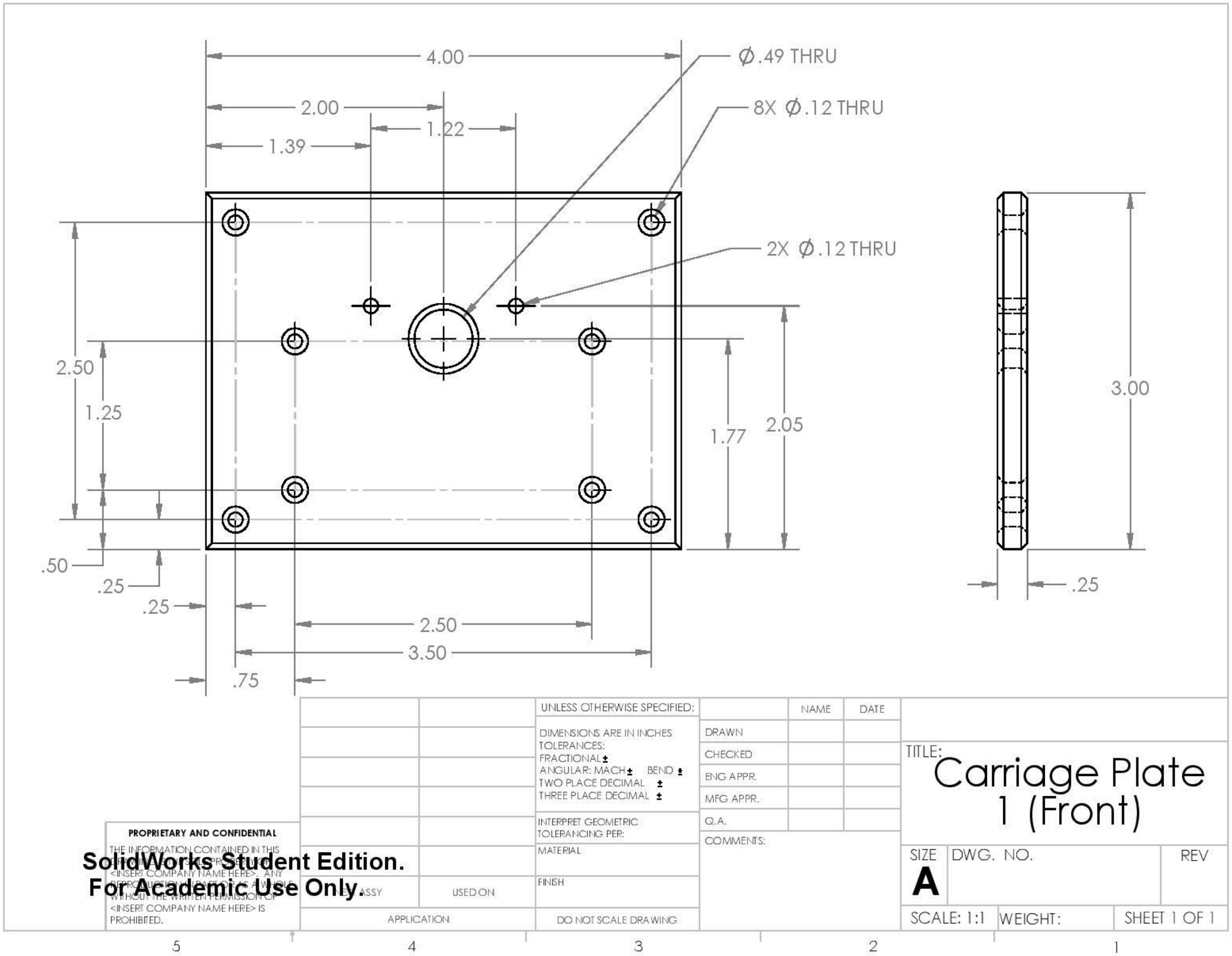
ITEM NO.	PART NUMBER	QTY.
1	Carriage Plate 1 (Front)	2
2	12v Pololu Motor	1
3	Coupler	1
4	4in Standoff	4
5	Wheel	4
6	Sleve Bearing	1
7	6mm aluminum shaft	1
8	Roller	4
9	sprocket gear	2
10	172:1 25D Gearmotor	1
11	Pololu 25D Motor Bracket	1
12	Angle Bracket	2
13	Top Plate	1
14	XL 1in Timing Pully	1
15	XL 2in Timing Pully	1
16	shaft collar	1
17	mounted bearing	2
18	timing belt	1

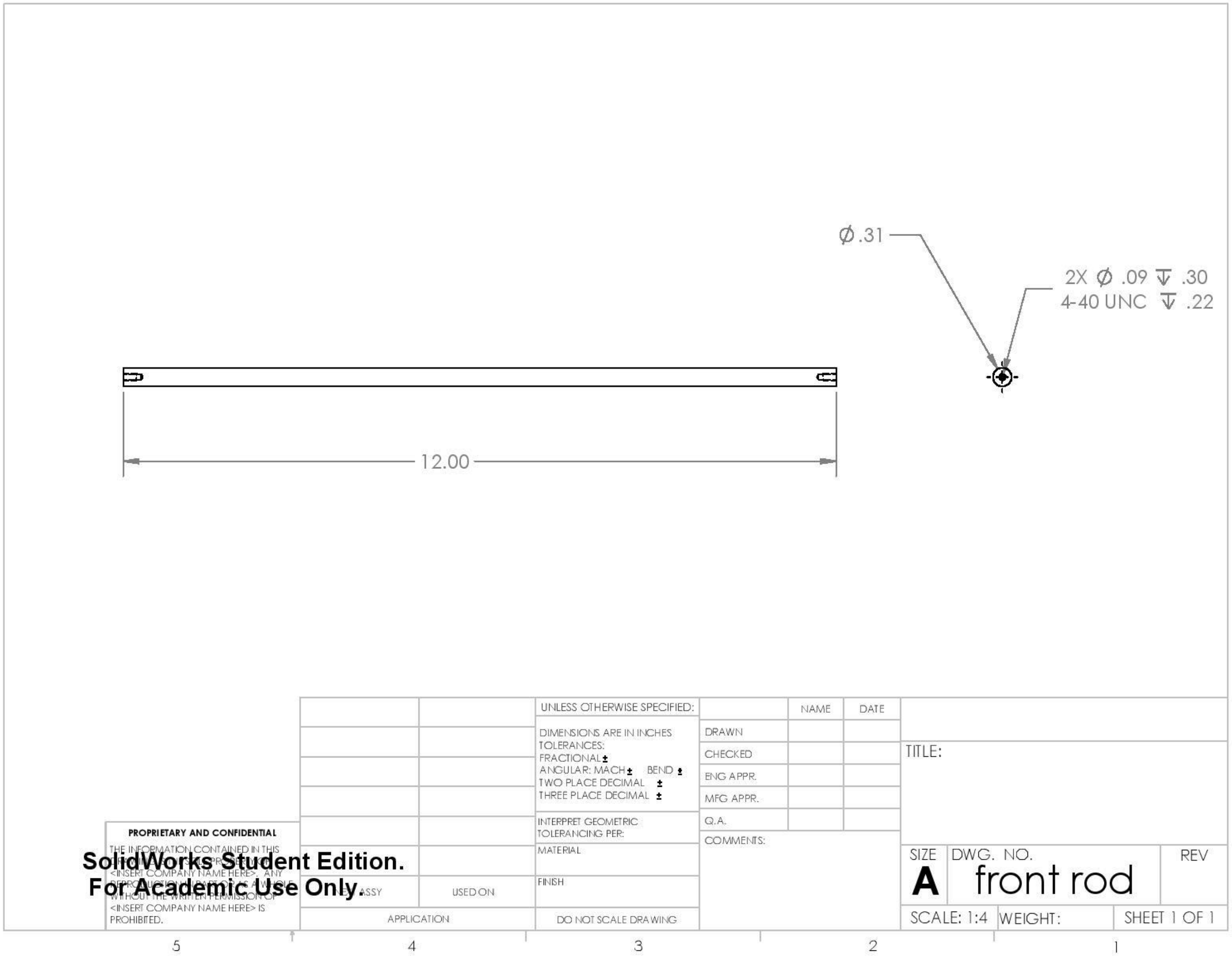

1.99
.49
.24
4X Ø.16
2X #4-40 Tapped Hole
3.25
4.00
.75
3.19
.13
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
Top Plate
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
NEXT ASSY
USED ON
APPLICATION
5
4
3
2
1

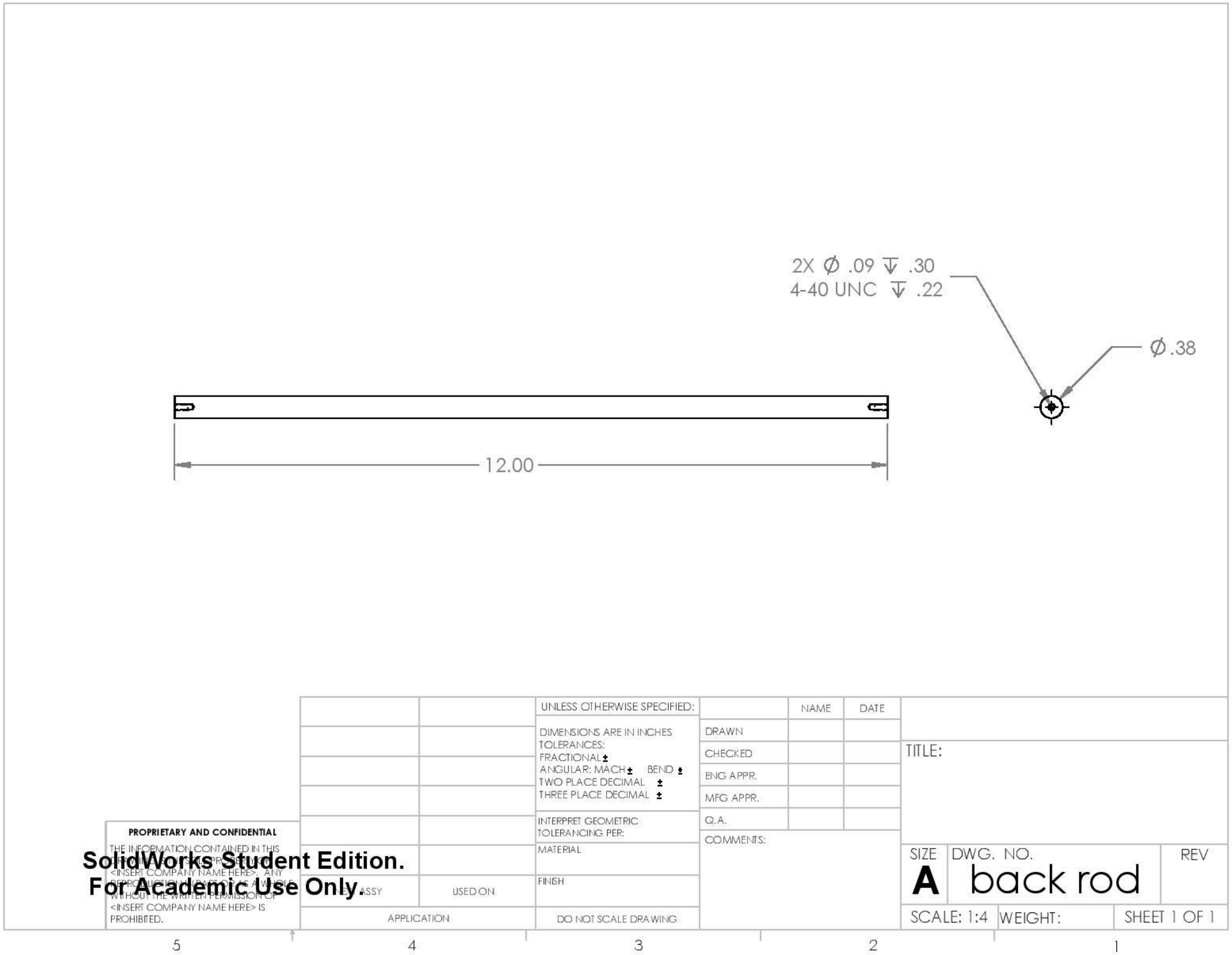

5.00
2X R.23
1.00
.15
4.00
4.50
.50
.50
2.50
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
U Channel
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
<INSERT COMPANY NAME HERE> IS PROHIBITED.
SolidWorks Student Edition.
For Academic Use Only.
5
4
3
2
1

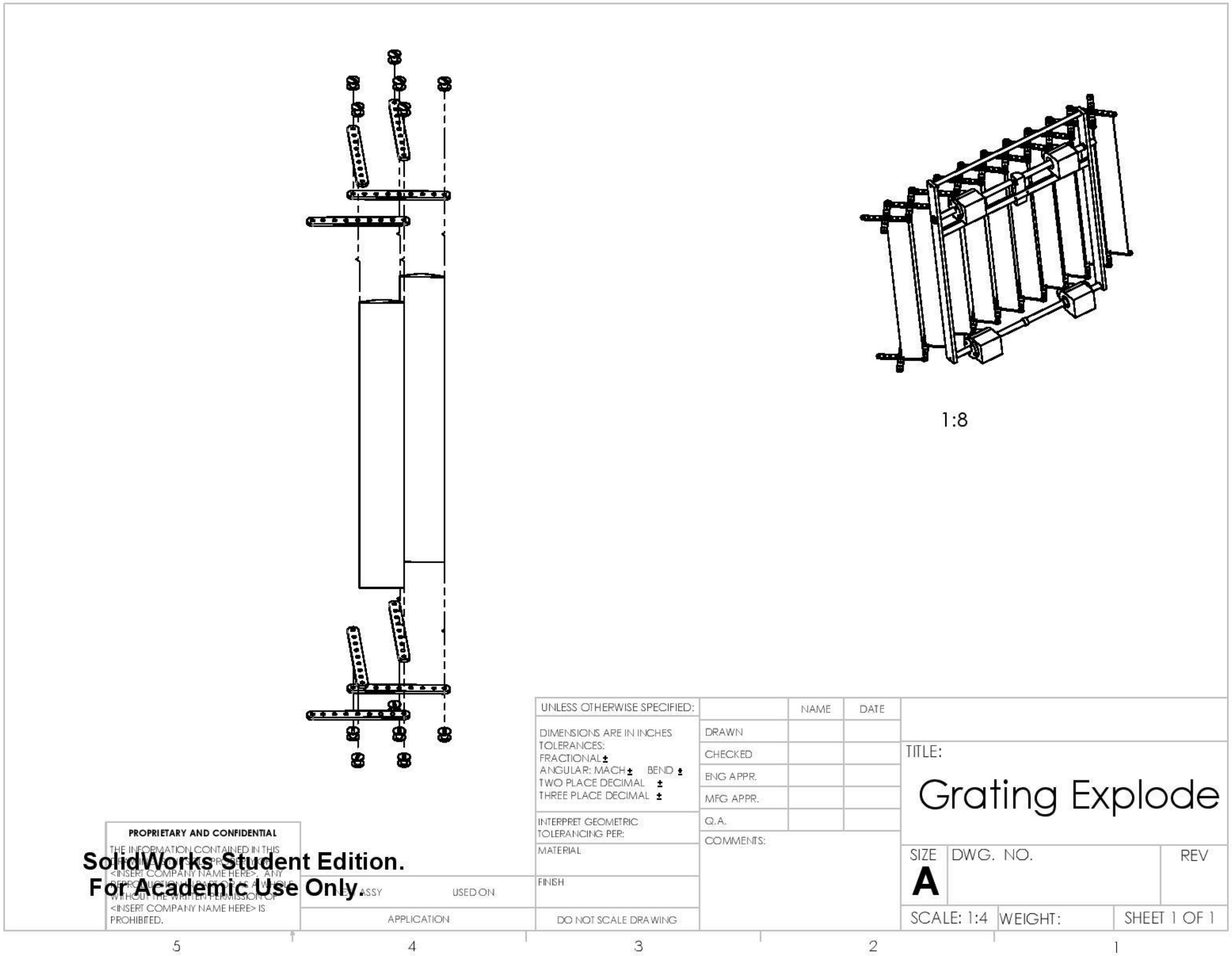

1:8
.22
5.02
1.00
Ø .09 ⟂ .30
4-40 UNC ⟂ .22
Ø .09 ⟂ .30
4-40 UNC ⟂ .22
.50
12.00
.20
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
motor support
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
<INSERT COMPANY NAME HERE> IS PROHIBITED.
5
4
3
2
1


NOTE: NON DIMENTIONED FEATURES
ARE ALL FROM STOCK PART
2.26
Ø.17
.61
Ø.10
Ø.10
.42
.42
.24
.24
1:2
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
REV
1088A320 Triangle Bracke
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
USED ON
APPLICATION
5
4
3
2
1


4.00
2.00
1.22
1.39
Ø.49 THRU
8X Ø.12 THRU
2X Ø.12 THRU
2.50
1.25
1.77
2.05
3.00
.50
.25
.25
.25
2.50
3.50
.75
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Carriage Plate 1 (Front)
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
USED ON
APPLICATION
5
4
3
2
1


Ø.31
2X Ø .09 ↧ .30
4-40 UNC ↧ .22
12.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
front rod
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
USED ON
APPLICATION
5
4
3
2
1


2X Ø .09 ↧ .30
4-40 UNC ↧ .22
Ø .38
12.00
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
PROPRIETARY AND CONFIDENTIAL
SolidWorks Student Edition.
For Academic Use Only.
USED ON
APPLICATION
DO NOT SCALE DRAWING
SIZE
A
DWG. NO.
back rod
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


1:8
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
APPLICATION
USED ON
NEXT ASSY
TITLE:
Grating Explode
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
SolidWorks Student Edition.
For Academic Use Only.
5
4
3
2
1

Appendix B: List of Vendors

Appendix C:
List of Vendors

McMaster Carr

(562) 692-5911

9630 Norwalk Blvd.
Santa Fe Springs, Ca 90670

http://www.mcmaster.com/#

Part Description	Component	Part Number	Quantity	Cost	Total Cost
Machine Screw	Beam Support	91772A110	1	$4.45	$4.45
Support Rods	Beam Support	8975K595	1	$6.34	$6.34
Bronze Flange Bearing	Beam Support	9440T15	2	$1.20	$2.40
Bearing for Back Rod	Beam Support	1688K8	4	$0.73	$2.92
Back Rod	Beam Support	8554K27	1	$0.95	$0.95
Front Rod	Beam Support	89535K86	1	$3.09	$3.09
Metal Plate motor support	Beam Support	8975K596	1	$3.00	$3.00
Small Threaded Bolt	Beam Support	98863A531	1	$5.65	$5.65
5/16 Shaft Collar	Beam Support	9946K12	1	$2.52	$2.52
Part Description	**Component**	**Part Number**	**Quantity**	**Cost**	**Total Cost**
Timing Belt	Flip Up	51514T512	1	$18.44	$18.44
Timing Pully on Motor	Flip Up	57105K13	1	$7.48	$7.48
Timing Pully on Shaft	Flip Up	57105K24	1	$8.75	$8.75
Part Description	**Component**	**Part Number**	**Quantity**	**Cost**	**Total Cost**
Shaft	Carriage	5395T113	1	$19.38	$19.38

Coupler (Stainless)	Carriage	5395T113	1	$8.95	$8.95
6mm>12mm PTFE Bearing	Carriage	2685T11	2	$3.55	$7.10
Roller Wheel	Carriage	9960T72	4	$4.04	$16.16
Faceplate (Undrilled) x 1 ft.	Carriage	8975K87	1	$7.46	$7.46
Standoffs	Carriage	91125A320	4	$4.64	$18.56
Spacer	Carriage	92825A147	1	$10.57	$10.57
Angle Bracket	Carriage	1088A32	2	$2.59	$5.18
Mounted Bearing for Support Frame	Carriage	5912K2	2	$10.33	$20.66
Metal Sprocket	Carriage	TD-099-011	2	$9.09	$18.18
Part Description	**Component**	**Part Number**	**Quantity**	**Cost**	**Total Cost**
Binding Posts (50 Pkg)	Scissors	93121A320	1	$10.44	$10.44
Better Tube Clamp	Scissors	3190T12	4	$3.54	$14.16
Part Description	**Component**	**Part Number**	**Quantity**	**Cost**	**Total Cost**
Tension Springs (3 PKG)	Buckle	9433K47	2	$6.87	13.74
Stainless Steel Clip	Buckle	3482T11	2	$7.93	15.86
Aluminum U Channel	Buckle	1630T33	1	$10.08	10.08
Rubber Strips, Soft (36")	Buckle	3207K11	1	$11.85	11.85
Eyebolt	Buckle	9489T512	6	$1.40	8.4
Part Description	**Component**	**Part Number**	**Quantity**	**Cost**	**Total Cost**
Medium-Strength Neoprene Rubber (6" X 36" x 3/32")	Fabric/Rails	8981K63	1	$13.90	$13.90
Elastic Fabric	Fabric/Rails	88225K61	2	$5.85	$11.70
Elastic Cord and Strap (25ft each)	Fabric/Rails	3937T43	2	$13.00	$26.00

Misumi
(847) 843-9105

1717 Penny Lane, Suite 200
Schaumburg, IL 60173

http://us.misumi-ec.com/

Part Description	Component	Part Number	Quantity	Cost	Total Cost
Left Handed Drive Shaft	Beam Supports	MTSTL10-160-MC3	1	$19.82	$19.82
Right Handed Drive Shaft	Beam Supports	MTSTR10-160-MC3	1	$19.82	$19.82
Part Description	**Component**	**Part Number**	**Quantity**	**Cost**	**Total Cost**
Lead Screw Nuts (Resin)	Scissors	MTSFJL10	2	$19.53	$39.06

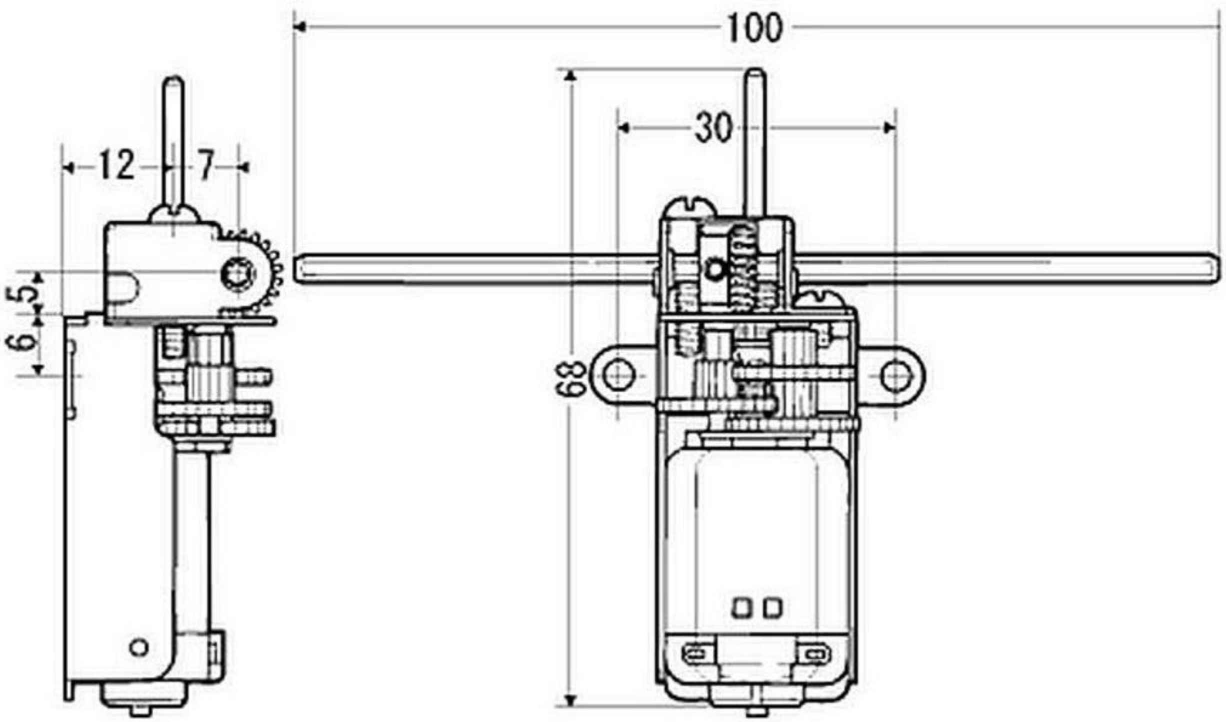
Pololu
(702) 262-6648

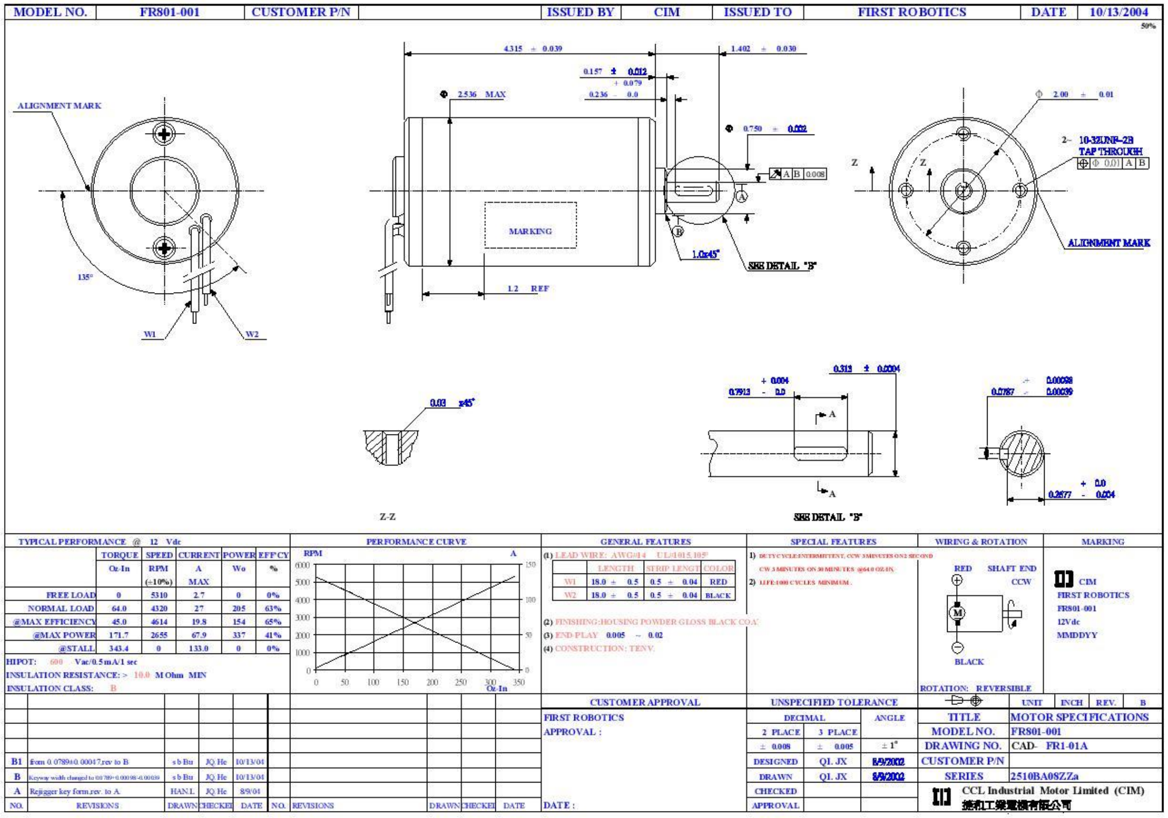
920 Pilot Rd.
Las Vegas, NV 89119

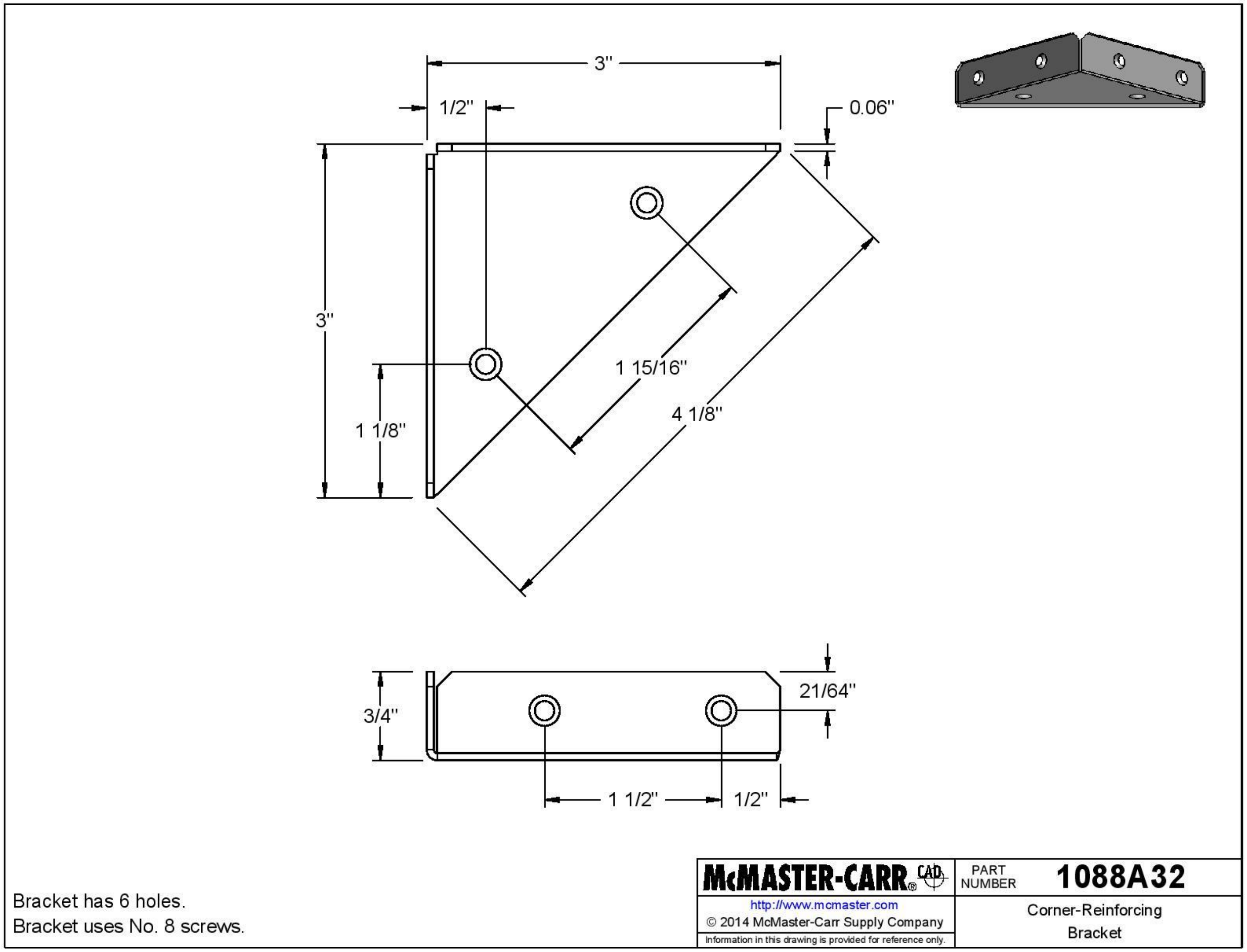
https://www.pololu.com/

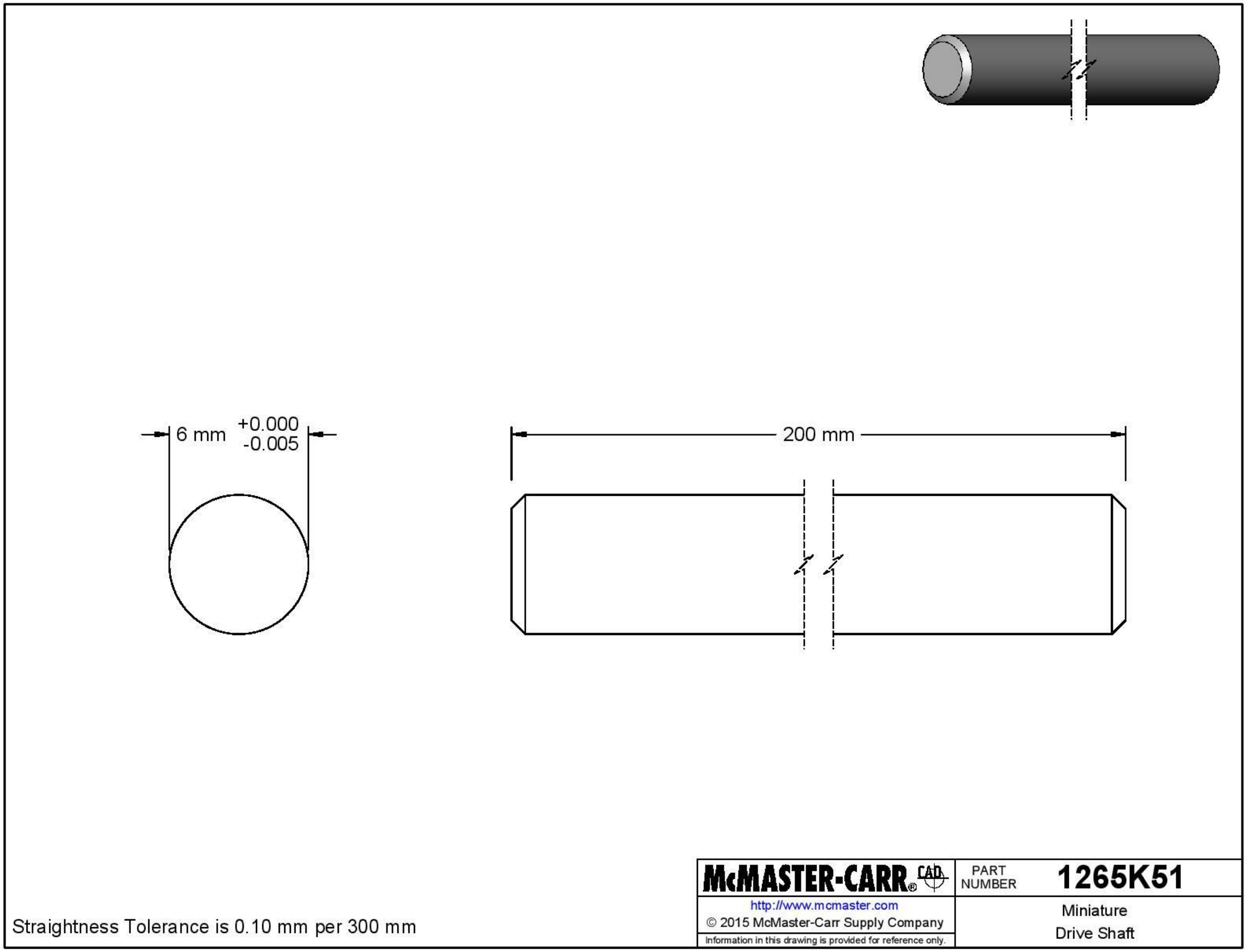
Part Description	Component	Part Number	Quantity	Cost	Total Cost
Pololu Metal Motor 25mm	Flip Up	1591	1	$19.95	$19.95
Part Description	**Component**	**Part Number**	**Quantity**	**Cost**	**Total Cost**
Motor (84 oz-in)	Carriage	1102	1	$24.95	$24.95
Part Description	**Component**	**Part Number**	**Quantity**	**Cost**	**Total Cost**
Small Geared Motors	Scissors	69	1	$7.59	$7.59
Part Description	**Component**	**Part Number**	**Quantity**	**Cost**	**Total Cost**
Dual High Power Motor Driver	Electronics	1213	1	$29.95	$29.95
Single Mid Power Motor Driver	Electronics	713	1	$4.95	$4.95

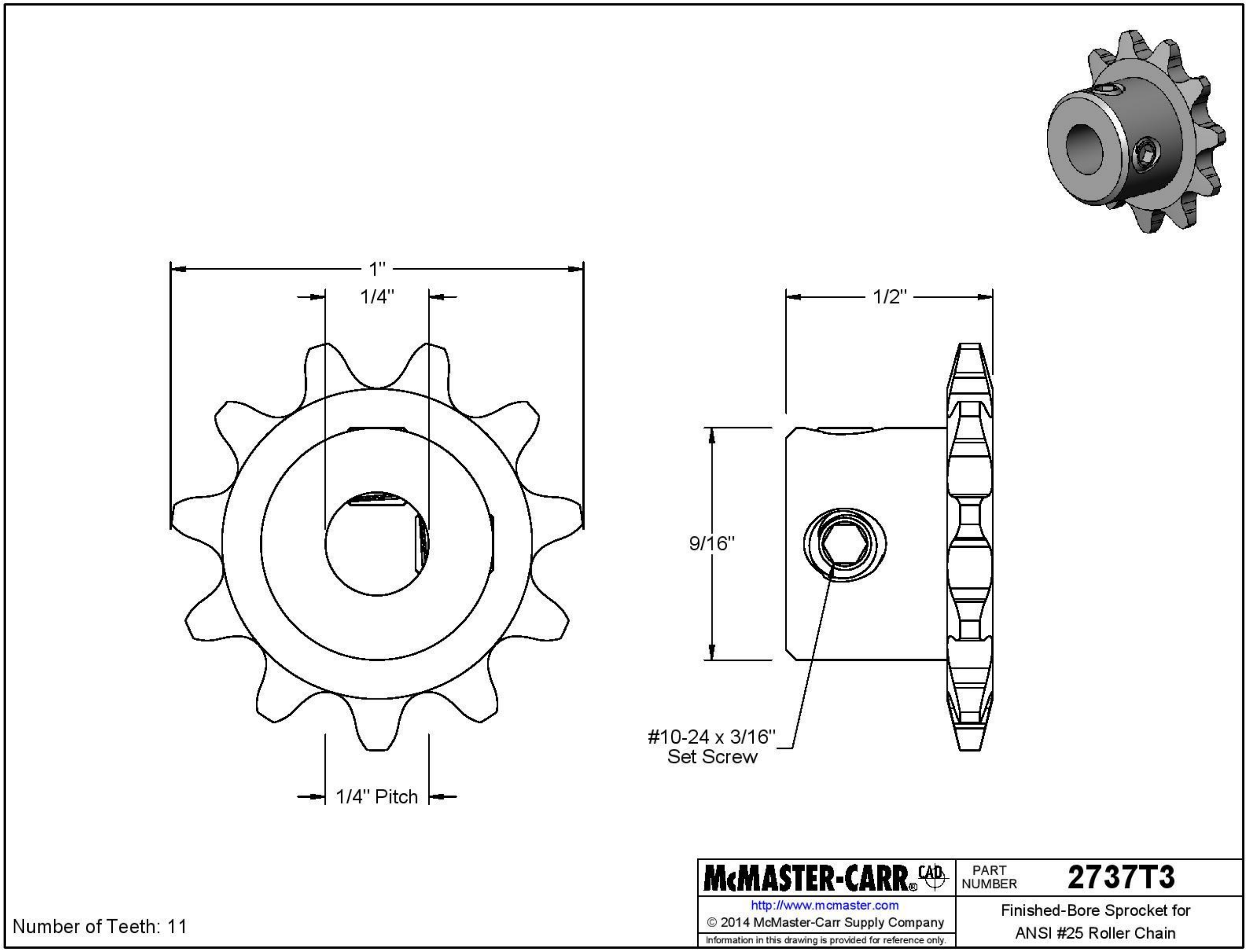
Appendix C: Available Part Drawings from the Manufacturer

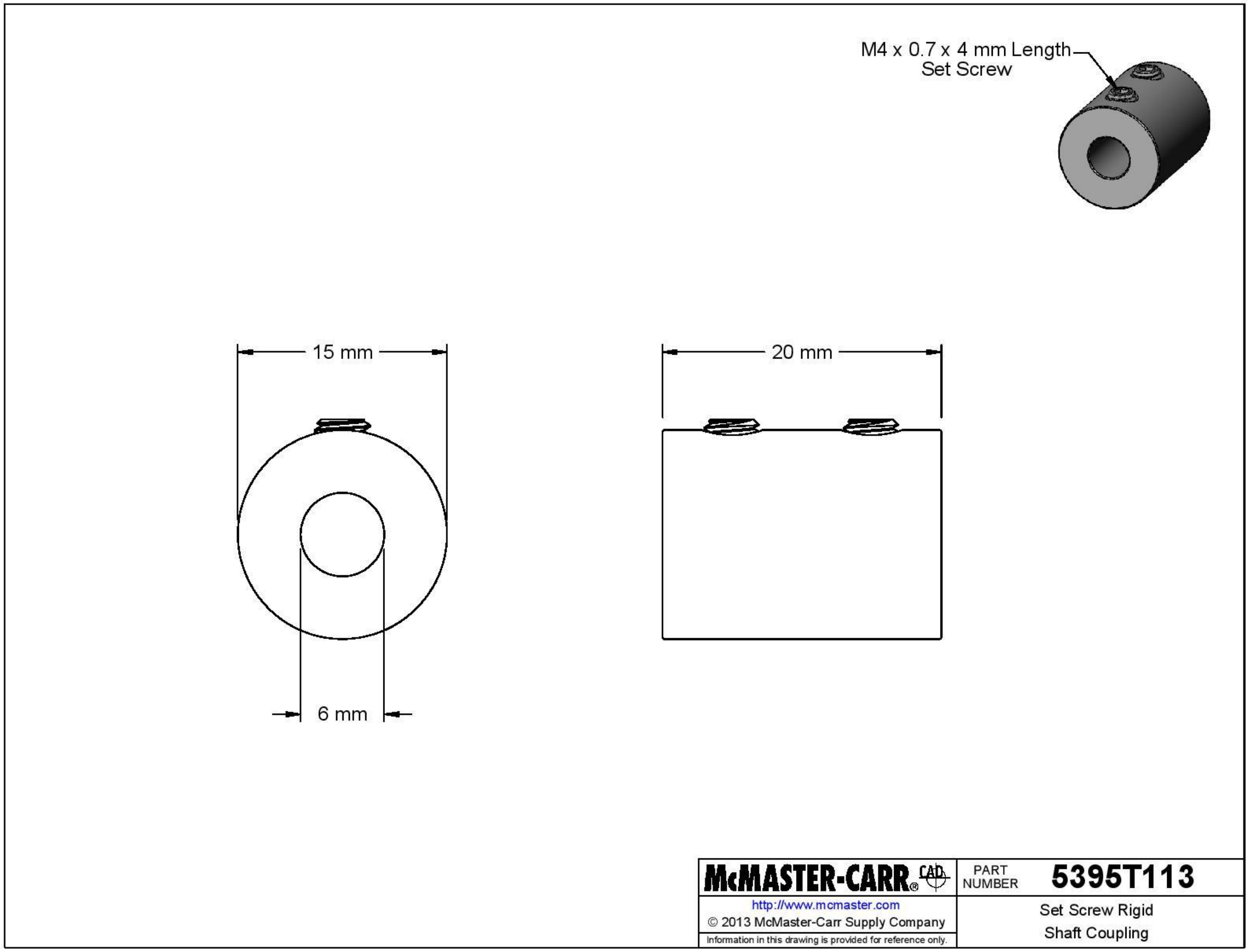

12
7
5
6
100
30
68

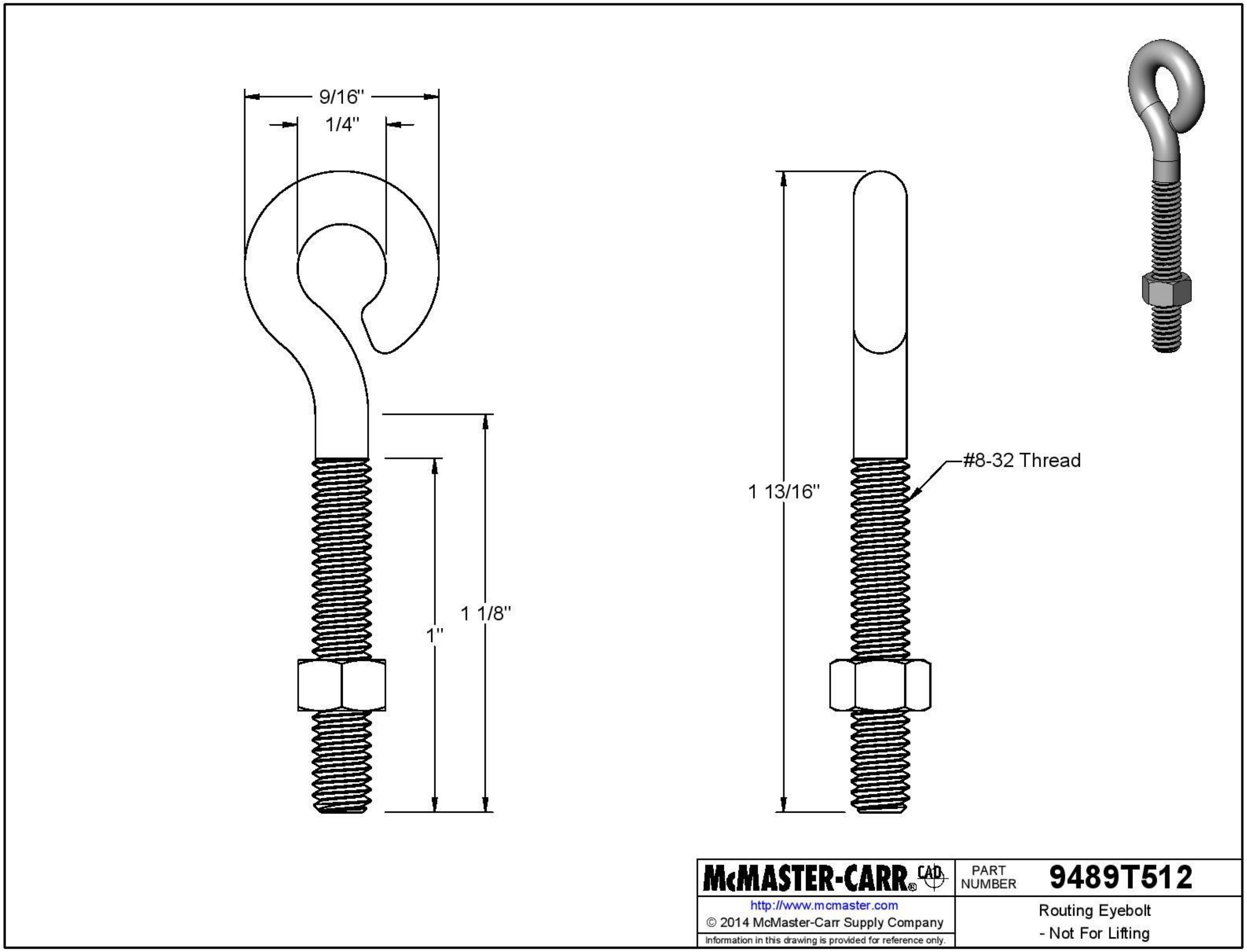

MODEL NO.
FR801-001
CUSTOMER P/N
ISSUED BY
CIM
ISSUED TO
FIRST ROBOTICS
DATE
10/13/2004
ALIGNMENT MARK
MARKING
SEE DETAIL "B"
Z-Z
TYPICAL PERFORMANCE @ 12 Vdc
PERFORMANCE CURVE
GENERAL FEATURES
SPECIAL FEATURES
WIRING & ROTATION
CUSTOMER APPROVAL
UNSPECIFIED TOLERANCE
TITLE
MOTOR SPECIFICATIONS
MODEL NO.
FR801-001
DRAWING NO.
CAD- FR1-01A
SERIES
2510BA08ZZa
CCL Industrial Motor Limited (CIM)

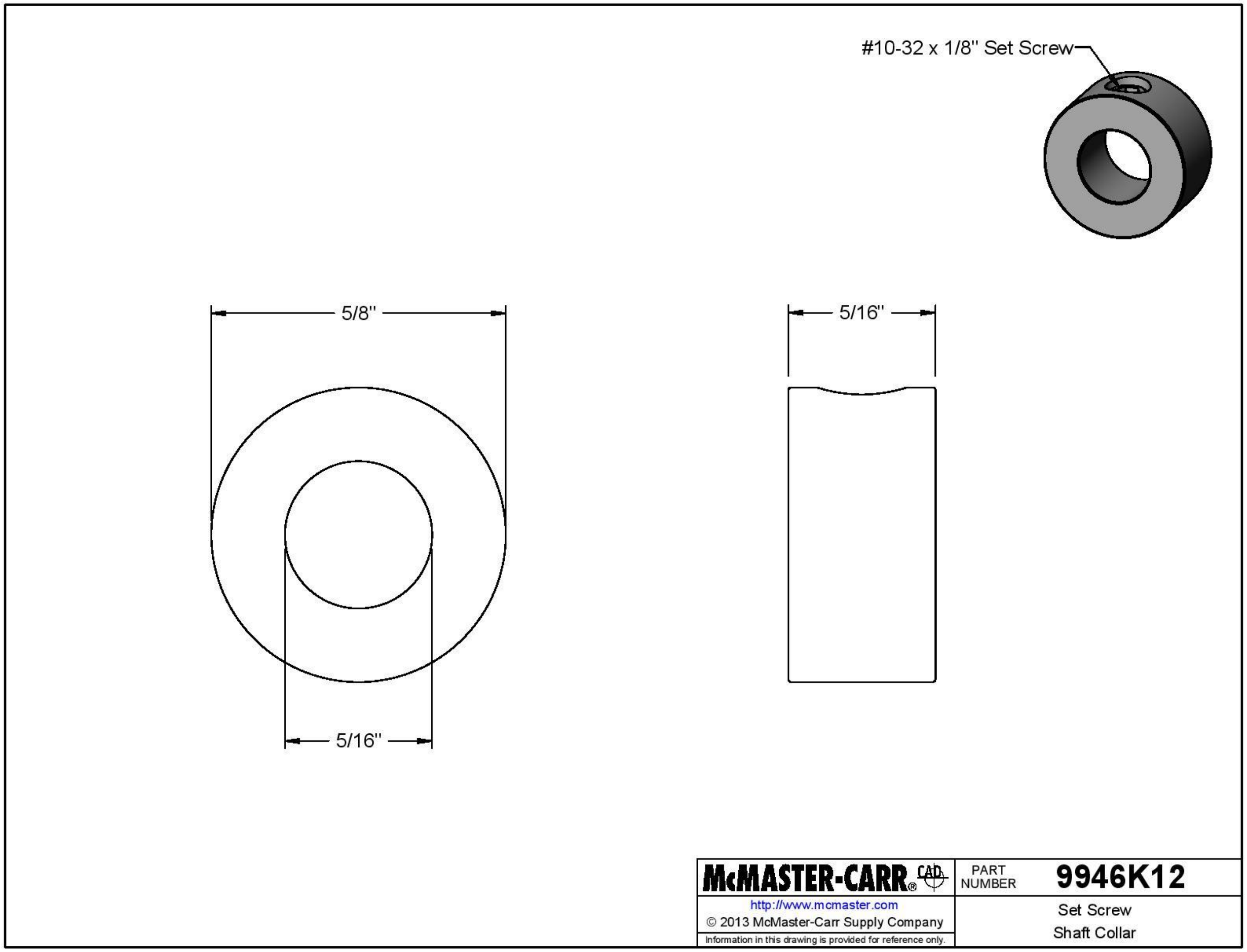

3"
1/2"
0.06"
3"
1 15/16"
1 1/8"
4 1/8"
21/64"
3/4"
1 1/2"
1/2"
Bracket has 6 holes.
Bracket uses No. 8 screws.
McMASTER-CARR
CAD
http://www.mcmaster.com
© 2014 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
PART NUMBER
1088A32
Corner-Reinforcing Bracket

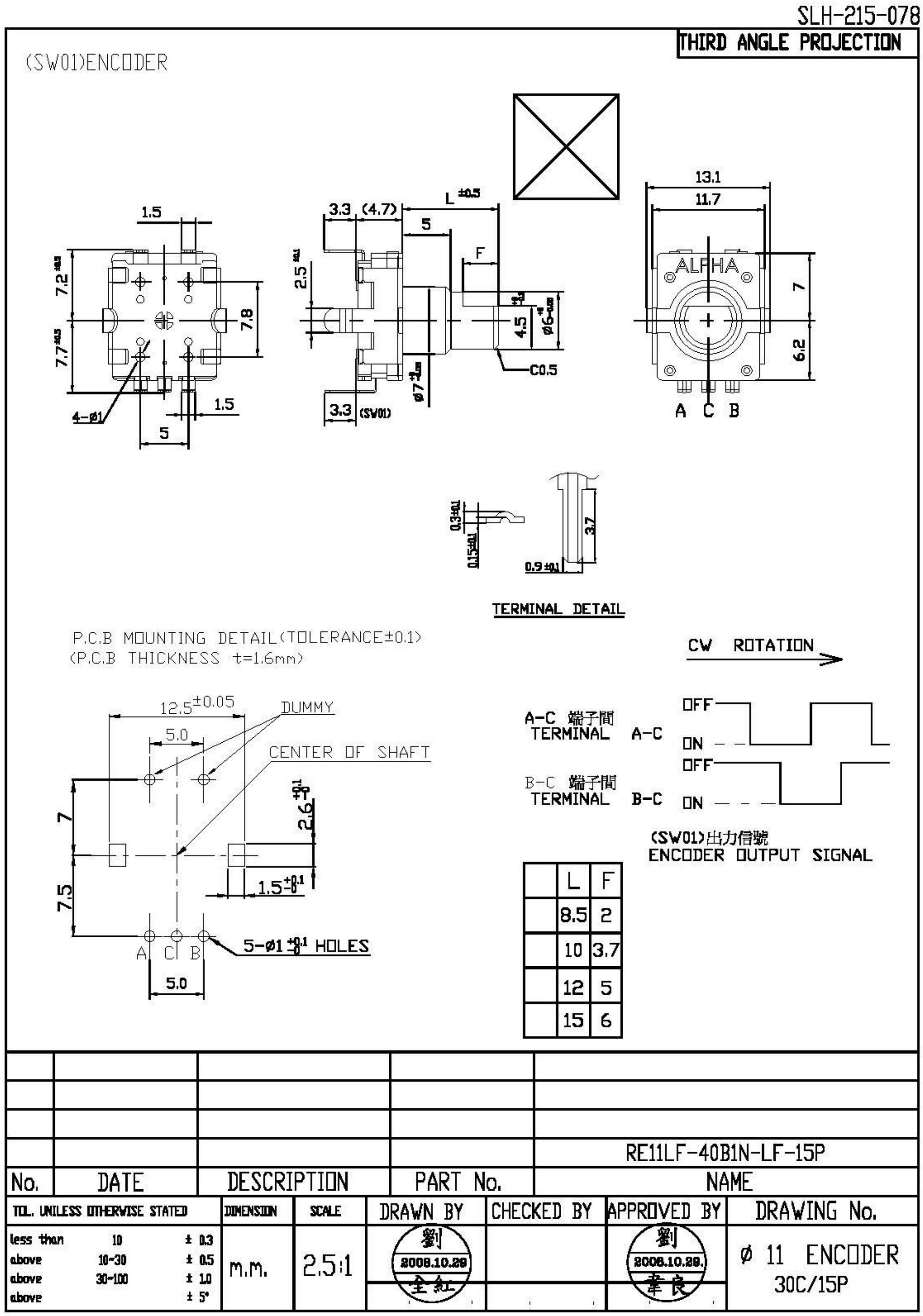

6 mm +0.000 -0.005
200 mm
Straightness Tolerance is 0.10 mm per 300 mm
McMASTER-CARR CAD
http://www.mcmaster.com
© 2015 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
PART NUMBER
1265K51
Miniature Drive Shaft


1"
1/4"
1/2"
9/16"
#10-24 x 3/16"
Set Screw
1/4" Pitch
Number of Teeth: 11
McMASTER-CARR CAD
http://www.mcmaster.com
© 2014 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
PART NUMBER
2737T3
Finished-Bore Sprocket for
ANSI #25 Roller Chain

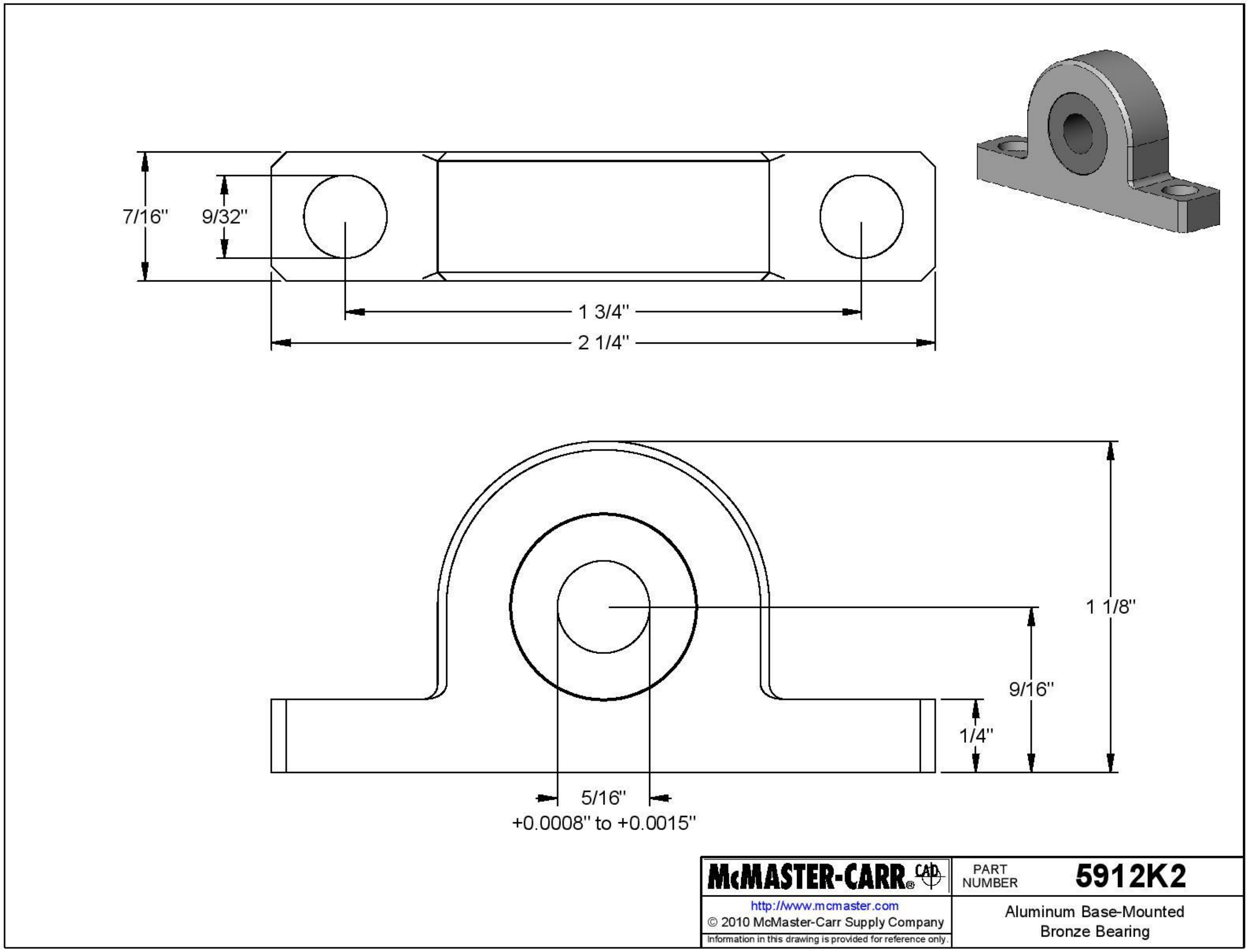

M4 x 0.7 x 4 mm Length
Set Screw
15 mm
20 mm
6 mm
McMASTER-CARR
PART NUMBER
5395T113
http://www.mcmaster.com
© 2013 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Set Screw Rigid
Shaft Coupling


9/16"
1/4"
1"
1 1/8"
1 13/16"
#8-32 Thread
McMASTER-CARR CAD
http://www.mcmaster.com
© 2014 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
PART NUMBER
9489T512
Routing Eyebolt
- Not For Lifting


#10-32 x 1/8" Set Screw
5/8"
5/16"
5/16"
McMASTER-CARR
CAD
PART NUMBER
9946K12
http://www.mcmaster.com
© 2013 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Set Screw
Shaft Collar



SLH-215-078
THIRD ANGLE PROJECTION
(SW01)ENCODER
ALPHA
A C B
TERMINAL DETAIL
P.C.B MOUNTING DETAIL(TOLERANCE±0.1)
(P.C.B THICKNESS t=1.6mm)
DUMMY
CENTER OF SHAFT
5-ø1 HOLES
CW ROTATION
A-C 端子間 TERMINAL
B-C 端子間 TERMINAL
OFF
ON
(SW01)出力信號
ENCODER OUTPUT SIGNAL
L F
8.5 2
10 3.7
12 5
15 6
RE11LF-40B1N-LF-15P
No. DATE DESCRIPTION PART No. NAME
TOL. UNLESS OTHERWISE STATED
less than 10 ± 0.3
above 10~30 ± 0.5
above 30~100 ± 1.0
above ± 5°
DIMENSION m.m.
SCALE 2.5:1
DRAWN BY
CHECKED BY
APPROVED BY
2008.10.29
DRAWING No.
ø 11 ENCODER
30C/15P



7/16"
9/32"
1 3/4"
2 1/4"
1 1/8"
9/16"
1/4"
5/16"
+0.0008" to +0.0015"
McMASTER-CARR
PART NUMBER
5912K2
http://www.mcmaster.com
© 2010 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Aluminum Base-Mounted Bronze Bearing

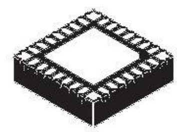
Freescale Semiconductor
Technical Data

Document Number: MC33926
Rev. 10.0, 8/2014

5.0 A Throttle Control H-Bridge

33926

AUTOMOTIVE THROTTLE H-BRIDGE ACTUATOR/ MOTOR EXCITER



Bottom View

PNB SUFFIX (Pb-FREE)
98ARL10579D
32-PIN PQFN

The 33926 is a SMARTMOS monolithic H-Bridge Power IC designed primarily for automotive electronic throttle control, but is applicable to any low-voltage DC servo motor control application within the current and voltage limits stated in this specification.

The 33926 is able to control inductive loads with currents up to 5.0 A peak. RMS current capability is subject to the degree of heatsinking provided to the device package. Internal peak-current limiting (regulation) is activated at load currents above 6.5 A ±1.5 A. Output loads can be pulse width modulated (PWM'ed) at frequencies up to 20 kHz. A load current feedback feature provides a proportional (0.24% of the load current) current output suitable for monitoring by a microcontroller's A/D input. A Status Flag output reports undervoltage, overcurrent, and overtemperature fault conditions.

Two independent inputs provide polarity control of two half-bridge totem-pole outputs. Two independent disable inputs are provided to force the H-Bridge outputs to tri-state (high-impedance off state). An inverted input changes the IN1 and IN2 inputs to LOW = true logic.

Features

- 5.0 to 28 V continuous operation (transient operation from 5.0 to 40 V)
- 225 mΩ maximum $R_{DS(on)}$ at 150 °C (each H-Bridge MOSFET)
- 3.0 V and 5.0 V TTL / CMOS logic compatible inputs
- Overcurrent limiting (Regulation) via an internal constant-off-time PWM
- Output short-circuit protection (short to V_{PWR} or ground)
- Temperature dependent current limit threshold reduction
- All Inputs have an internal source/sink to define the default (floating input) states
- Sleep mode with current draw < 50 µA (with inputs floating or set to match default logic states)

Applications

- Electronic Throttle Control (ETC)
- Exhaust Gas Recirculation (EGR)
- Turbo Flap Control
- Industrial and Medical pumps and motor control

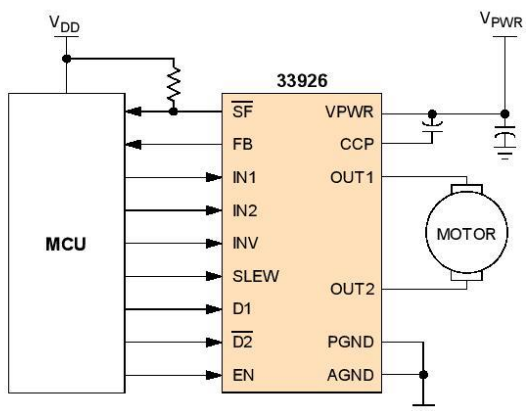
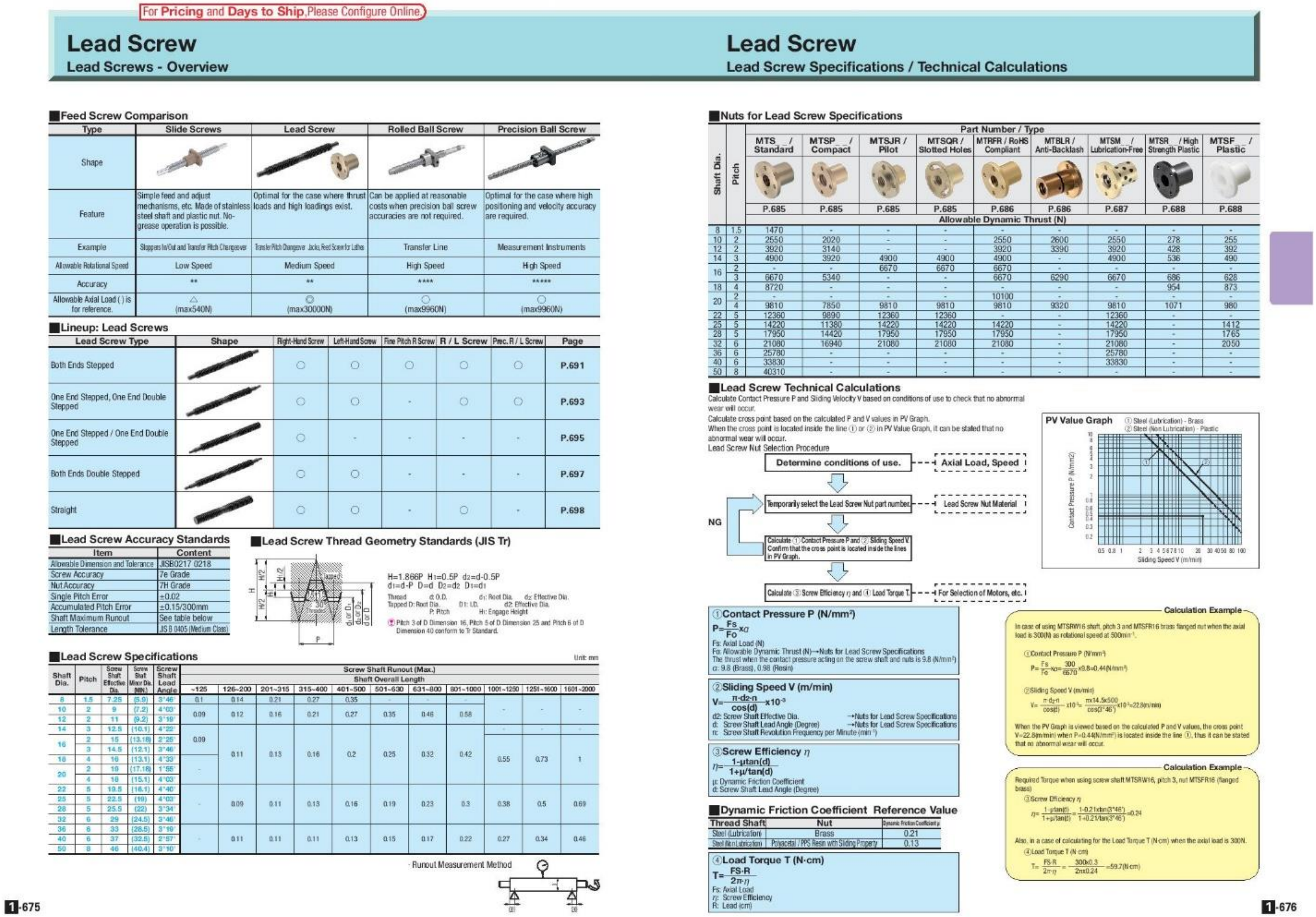


Figure 1. 33926 Simplified Application Diagram



For Pricing and Days to Ship, Please Configure Online.

Lead Screw

Lead Screws - Overview

Feed Screw Comparison

Type	Slide Screws	Lead Screw	Rolled Ball Screw	Precision Ball Screw
Shape				
Feature	Simple feed and adjust mechanisms, etc. Made of stainless steel shaft and plastic nut. No-grease operation is possible.	Optimal for the case where thrust loads and high loadings exist.	Can be applied at reasonable costs when precision ball screw accuracies are not required.	Optimal for the case where high positioning and velocity accuracy are required.
Example	Stoppers In/Out and Transfer Pitch Changeover	Transfer Pitch Changeover Jacks, Feed Screw for Lathes	Transfer Line	Measurement Instruments
Allowable Rotational Speed	Low Speed	Medium Speed	High Speed	High Speed
Accuracy	**	**	****	*****
Allowable Axial Load ( ) is for reference.	△ (max540N)	◎ (max30000N)	○ (max9960N)	○ (max9960N)

Lineup: Lead Screws

Lead Screw Type	Shape	Right-Hand Screw	Left-Hand Screw	Fine Pitch R Screw	R / L Screw	Prec. R / L Screw	Page
Both Ends Stepped		○	○	○	○	○	P.691
One End Stepped, One End Double Stepped		○	○	-	○	○	P.693
One End Stepped / One End Double Stepped		○	-	-	-	-	P.695
Both Ends Double Stepped		○	○	-	-	-	P.697
Straight		○	○	-	○	-	P.698

Lead Screw Accuracy Standards

Item	Content
Allowable Dimension and Tolerance	JISB0217 0218
Screw Accuracy	7e Grade
Nut Accuracy	7H Grade
Single Pitch Error	±0.02
Accumulated Pitch Error	±0.15/300mm
Shaft Maximum Runout	See table below
Length Tolerance	JIS B 0405 (Medium Class)

Lead Screw Thread Geometry Standards (JIS Tr)

H=1.866P H1=0.5P d2=d-0.5P
d1=d-P D=d D2=d2 D1=d1

Thread d: O.D. d1: Root Dia. d2: Effective Dia.
Tapped D: Root Dia. D1: I.D. D2: Effective Dia.
P: Pitch H1: Engage Height

Pitch 3 of D Dimension 16, Pitch 5 of D Dimension 25 and Pitch 6 of D Dimension 40 conform to Tr Standard.

Lead Screw Specifications

Unit: mm

Shaft Dia.	Pitch	Screw Shaft Effective Dia.	Screw Shaft Minor Dia. (MIN)	Screw Shaft Lead Angle	Screw Shaft Runout (Max.) Shaft Overall Length ~125	126~200	201~315	315~400	401~500	501~630	631~800	801~1000	1001~1250	1251~1600	1601~2000
8	1.5	7.25	(5.9)	3°46'	0.1	0.14	0.21	0.27	0.35	-	-	-	-	-	-
10	2	9	(7.2)	4°03'	0.09	0.12	0.16	0.21	0.27	0.35	0.46	0.58	-	-	-
12	2	11	(9.2)	3°19'											
14	3	12.5	(10.1)	4°22'											
16	2	15	(13.18)	2°26'	0.09	0.11	0.13	0.16	0.2	0.25	0.32	0.42	0.55	0.73	1
16	3	14.5	(12.1)	3°46'											
18	4	16	(13.1)	4°33'											
20	2	19	(17.18)	1°55'	-										
20	4	18	(15.1)	4°03'											
22	5	19.5	(16.1)	4°40'	-	0.09	0.11	0.13	0.16	0.19	0.23	0.3	0.38	0.5	0.69
25	5	22.5	(19)	4°03'											
28	5	25.5	(22)	3°34'											
32	6	29	(24.5)	3°46'	-	0.11	0.11	0.11	0.13	0.15	0.17	0.22	0.27	0.34	0.46
36	6	33	(28.5)	3°19'											
40	6	37	(32.5)	2°57'											
50	8	46	(40.4)	3°10'											

· Runout Measurement Method

1-675

Lead Screw

Lead Screw Specifications / Technical Calculations

Nuts for Lead Screw Specifications

Part Number / Type; Allowable Dynamic Thrust (N)

Shaft Dia.	Pitch	MTS / Standard P.685	MTSP / Compact P.685	MTSJR / Pilot P.685	MTSQR / Slotted Holes P.685	MTRFR / RoHS Compliant P.686	MTBLR / Anti-Backlash P.686	MTSM / Lubrication-Free P.687	MTSR / High Strength Plastic P.688	MTSF / Plastic P.688
8	1.5	1470	-	-	-	-	-	-	-	-
10	2	2550	2020	-	-	2550	2600	2550	278	255
12	2	3920	3140	-	-	3920	3390	3920	428	392
14	3	4900	3920	4900	4900	4900	-	4900	536	490
16	2	-	-	6670	6670	6670	-	-	-	-
16	3	6670	5340	-	-	6670	6290	6670	686	628
18	4	8720	-	-	-	-	-	-	954	873
20	2	-	-	-	-	10100	-	-	-	-
20	4	9810	7850	9810	9810	9810	9320	9810	1071	980
22	5	12360	9890	12360	12360	-	-	12360	-	-
25	5	14220	11380	14220	14220	14220	-	14220	-	1412
28	5	17950	14420	17950	17950	17950	-	17950	-	1765
32	6	21080	16940	21080	21080	21080	-	21080	-	2050
36	6	25780	-	-	-	-	-	25780	-	-
40	6	33830	-	-	-	-	-	33830	-	-
50	8	40310	-	-	-	-	-	-	-	-

Lead Screw Technical Calculations

Calculate Contact Pressure P and Sliding Velocity V based on conditions of use to check that no abnormal wear will occur.
Calculate cross point based on the calculated P and V values in PV Graph.
When the cross point is located inside the line ① or ② in PV Value Graph, it can be stated that no abnormal wear will occur.
Lead Screw Nut Selection Procedure

Determine conditions of use. → Axial Load, Speed
Temporarily select the Lead Screw Nut part number. → Lead Screw Nut Material
Calculate ① Contact Pressure P and ② Sliding Speed V. Confirm that the cross point is located inside the lines in PV Graph. (NG → back to selection)
Calculate ③ Screw Efficiency η and ④ Load Torque T. → For Selection of Motors, etc.

PV Value Graph: ① Steel (Lubrication) - Brass; ② Steel (Non Lubrication) - Plastic; Contact Pressure P (N/mm²); Sliding Speed V (m/min)

① Contact Pressure P (N/mm²)

$P=\frac{Fs}{Fo}\times\alpha$

Fs: Axial Load (N)
Fo: Allowable Dynamic Thrust (N) → Nuts for Lead Screw Specifications
The thrust when the contact pressure acting on the screw shaft and nuts is 9.8 (N/mm²)
α: 9.8 (Brass), 0.98 (Resin)

② Sliding Speed V (m/min)

$V=\frac{\pi \cdot d_2 \cdot n}{\cos(d)}\times10^{-3}$

d2: Screw Shaft Effective Dia. → Nuts for Lead Screw Specifications
d: Screw Shaft Lead Angle (Degree) → Nuts for Lead Screw Specifications
n: Screw Shaft Revolution Frequency per Minute (min⁻¹)

③ Screw Efficiency η

$\eta=\frac{1-\mu\tan(d)}{1+\mu/\tan(d)}$

μ: Dynamic Friction Coefficient
d: Screw Shaft Lead Angle (Degree)

Dynamic Friction Coefficient Reference Value

Thread Shaft	Nut	Dynamic Friction Coefficient μ
Steel (Lubrication)	Brass	0.21
Steel (Non Lubrication)	Polyacetal / PPS Resin with Sliding Property	0.13

④ Load Torque T (N·cm)

$T=\frac{FS \cdot R}{2\pi \cdot \eta}$

Fs: Axial Load
η: Screw Efficiency
R: Lead (cm)

Calculation Example

In case of using MTSRW16 shaft, pitch 3 and MTSFR16 brass flanged nut when the axial load is 300(N) as rotational speed at 500min⁻¹.

① Contact Pressure P (N/mm²)

$P=\frac{Fs}{Fo}\times\alpha=\frac{300}{6670}\times9.8=0.44(N/mm^2)$

② Sliding Speed V (m/min)

$V=\frac{\pi \cdot d_2 \cdot n}{\cos(d)}\times10^{-3}=\frac{\pi\times14.5\times500}{\cos(3°46')}\times10^{-3}=22.8(m/min)$

When the PV Graph is viewed based on the calculated P and V values, the cross point V=22.8(m/min) when P=0.44(N/mm²) is located inside the line ①, thus it can be stated that no abnormal wear will occur.

Calculation Example

Required Torque when using screw shaft MTSRW16, pitch 3, nut MTSFR16 (flanged brass)

③ Screw Efficiency η

$\eta=\frac{1-\mu\tan(d)}{1+\mu/\tan(d)}=\frac{1-0.21\times\tan(3°46')}{1+0.21/\tan(3°46')}=0.24$

Also, in a case of calculating for the Load Torque T (N·cm) when the axial load is 300N.

④ Load Torque T (N·cm)

$T=\frac{FS \cdot R}{2\pi \cdot \eta}=\frac{300\times0.3}{2\pi\times0.24}=59.7(N\cdot cm)$

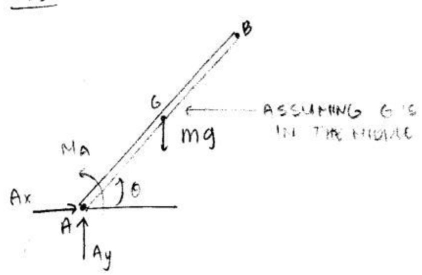
1-676

Appendix D: Hand Calculations

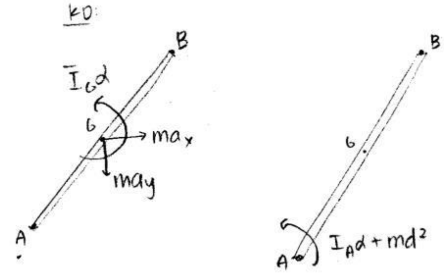
WANT:
→ REACH ANY POSITION WITHIN 10 SECONDS
→ ANGLE: $0° \le \theta \le 270°$

FOR AN ARBITRARY ANGLE:

FBD



KD:



SUM OF THE MOMENTS ABOUT G

$$\circlearrowleft \Sigma M_G = \bar{I}_G \alpha$$

$$M_A - A_y\left(\frac{L_g}{2}\cos\theta\right) + A_x\left(\frac{L_g}{2}\sin\theta\right) = \bar{I}_G\alpha$$

SOLVING FOR M_A

$$M_A = A_y\left(\frac{L_g}{2}\cos\theta\right) - A_x\left(\frac{L_g}{2}\sin\theta\right) + \bar{I}_G\alpha$$

MOTOR TORQUE

SUM OF THE FORCES

$$\rightarrow \Sigma F_x = ma_x \qquad \uparrow \Sigma F_y = ma_y$$

$$A_x = ma_x \qquad A_y - mg = ma_y$$

$$A_y = m(g + a_y)$$

→ INITIALLY AT REST SO $\omega_0 = 0$ rad/s
→ ASSUMING UNIFORMLY ACCELERATED ROTATION
α = CONSTANT

$$\omega = \omega_0^{\,0} + \alpha t$$

$$\theta = \theta_0^{\,0} + \omega_0^{\,0} t + \frac{1}{2}\alpha t^2$$

$$\theta = \frac{1}{2}\alpha t^2$$

$$\alpha = \frac{2\theta}{t^2}$$

$\theta_{max} = 270°$
$t_{max} = 10s$

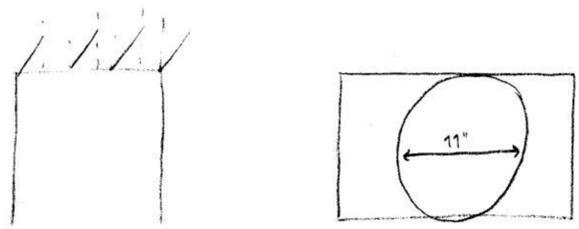
IF α = CONSTANT

$$\alpha = \frac{2(270°)}{(10s)^2}\left(\frac{\pi \text{ rad}}{180°}\right)$$

$$\alpha = 0.094 \text{ rad/s}^2$$

GRATING GEOMETRY

→ MINIMUM OF 3 BARS NEEDED

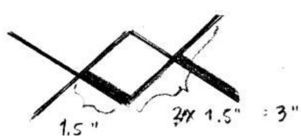


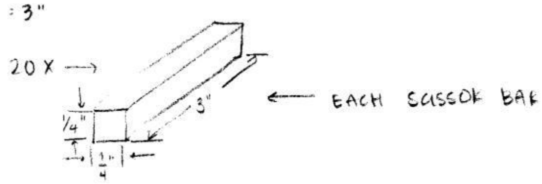
BAR WIDTH:

→ SMALLEST ANGLE WHEN FULLY EXTENDED ~ 10°

$$\left(\frac{11"}{7}\right)\left(\frac{1}{\cos 10°}\right) \approx 1.6"$$

$$W_{bar} \approx 1.50"$$





SCISSORS

VOLUME (TOTAL):

$$V = 20 \times \left(3in \times \tfrac{1}{4}in \times \tfrac{1}{4}in\right)$$

$$V = 3.75 in^3$$

ALUMINUM BARS:

$$\rho_{Al} = 0.098\ lb_m/in^3$$

$$m_{Al} = \rho_{Al} V$$

$$= 0.098\ lb_m/in^3\ (3.75 in^3)$$

$$m_{Al} = 0.3675\ lb_m$$

$$W_{Al} = 0.3675\ lb_m \left(\frac{1\ lb_f}{1\ lb_m\ 32.2 ft/s^2}\right)(32.2 ft/s^2)$$

$$W_{Al} = 0.3675\ lb_f$$

ABS BARS:

$$\rho_{ABS} = 0.0376\ lb_m/in^3$$

$$m_{ABS} = \rho_{ABS} V$$

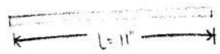
$$= 0.0376\ lb_m/in^3\ (3.75 in^3)$$

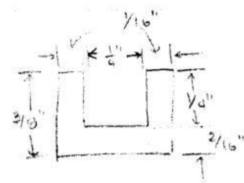
$$m_{ABS} = 0.141\ lb_m$$

$$W_{ABS} = 0.141\ lb_m \left(\frac{1\ lb_f}{1\ lb_m\ 32.2 ft/s^2}\right)(32.2 ft/s^2)$$

$$W_{ABS} = 0.141\ lb_f$$

GUIDING RAILS





CROSS SECTIONAL AREA

$$A = 2 \times \left(\frac{1}{16} \text{ in} \times \frac{3}{8} \text{ in}\right) + \left(\frac{1}{4} \text{ in} \times \frac{2}{16} \text{ in}\right)$$

$$A = 0.078125 \text{ in}^2$$

VOLUME

$$V = AL$$
$$= 0.078125 \text{ in}^2 (11 \text{ in})$$
$$V = 0.8594 \text{ in}^3$$

ALUMINUM RAILS

$$\rho_{Al} = 0.098 \text{ lb}_m/\text{in}^3$$
$$m_{Al} = \rho_{Al} V$$
$$= (0.098 \text{ lb}_m/\text{in}^3)(0.8594 \text{ in}^3)$$
$$m_{Al} = 0.084 \text{ lb}_m$$

$$W_{Al} = 0.084 \text{ lb}_m \left(\frac{1 \text{ lb}_f}{1 \text{ lb}_m \cdot 32.2 \text{ ft/s}^2}\right)(32.2 \text{ ft/s}^2)$$

$$W_{Al} = 0.084 \text{ lb}_f$$

ABS RAILS

$$\rho_{ABS} = 0.0376 \text{ lb}_m/\text{in}^3$$
$$m_{ABS} = \rho_{ABS} V$$
$$= 0.0376 \text{ lb}_m/\text{in}^3 (0.8594 \text{ in}^3)$$
$$= 0.0323 \text{ lb}_m$$

$$W_{ABS} = 0.0323 \text{ lb}_m \left(\frac{1 \text{ lb}_f}{1 \text{ lb}_m \cdot 32.2 \text{ ft/s}^2}\right)(32.2 \text{ ft/s}^2)$$

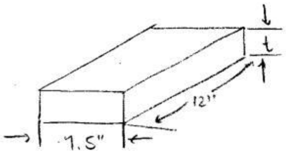
$$W_{ABS} = 0.0323 \text{ lb}_f$$

(

FROM KELLY'S CALCULATIONS:
FOR THE GRATING BARS

$t_{Al} = 0.16in$

$t_{ABS} = 0.64in$



ALUMINUM GRATING BARS:

$V = 0.16in \times 12in \times 1.5in$

$V = 2.88in^3$

$\rho_{Al} = 0.098 lbm/in^3$

$m_{Al} = \rho_{Al} V$

$= (0.098 lbm/in^3)(2.88in^3)$

$m_{Al} = 0.282 lb_m$

$W_{Al} = 0.282 lbm \left(\frac{1 lbf}{1 lbm \cdot 32.2 ft/s^2}\right)(32.2 ft/s^2)$

$W_{Al} = 0.282 lbf$ ← WEIGHT OF ONE BAR

TOTAL WEIGHT (10 BARS)

$W_{Al} = 10 \times (0.282 lbf)$

$W_{Al} = 2.82 lbf$

ABS GRATING BARS

$V: 0.64in \times 12in \times 1.5in$

$V: 11.52 in^3$

$\rho_{ABS} = 0.0376 lb m/in^3$

$m_{ABS} = \rho_{ABS} V$

$= (0.0376 lbm/in^3)(11.52 in^3)$

$m_{ABS} = 0.433 lb_m$

$W_{ABS} = 0.433 lbm \left(\frac{1 lbf}{1 lbm \cdot 32.2 ft/s^2}\right)(32.2 ft/s^2)$

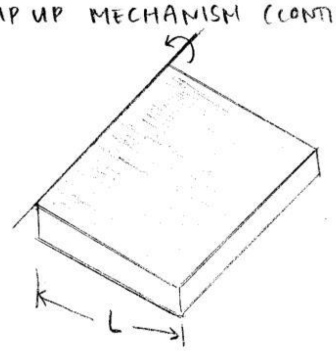
$W_{ABS} = 0.433 lb_m$ ← WEIGHT OF ONE BAR

TOTAL WEIGHT (10 BARS)

$W_{ABS} = 10 \times (0.433 lbf)$

$W_{ABS} = 4.33 lbf$

FLIP UP MECHANISM (CONTINUED...)



THIN RECTANGULAR PLATE ROTATING ABOUT ONE EDGE

$I = \frac{1}{3}mA^2$, $A = L = 12in$

*ASSUMING WE CAN TREAT THE WEIGHT OF THE GRATING AS ONE PLATE/BLOCK

$I = \frac{1}{3}mL^2$

MOMENT ABOUT A USING THE PARALLEL AXIS THEOREM

$\circlearrowleft \Sigma M_A = I_A \alpha$

* $m = m_{TOTAL}$

$M_A - mg\left(\frac{Lg}{2}\cos\theta\right) = \frac{1}{3}mA^2\alpha$

$M_A = mg\left(\frac{Lg}{2}\cos\theta\right) + \frac{1}{3}mA^2\alpha$

$M_A = mg\frac{Lg}{2}\cos\theta + \frac{1}{3}mL^2\alpha$

TOTAL MASS, ASSUMING:
- 2 PAIRS OF SCISSORS
- \+ 2 SETS OF RAILS
- \+ GRATING BARS

ALSO ASSUMING ALL MASS IS CONCENTRATED IN THE MIDDLE

ALUMINUM:

$m_{TOT} = (2 \times 0.3675 lb_m) + (2 \times 0.084 lb_m) + 2.82 lb_f$

$m_{TOT} = 3.723 lb_m$

ABS:

$m_{TOT} = (2 \times 0.141 lb_m) + (2 \times 0.0323 lb_m) + 4.33 lb_m$

$m_{TOT} = 4.6766 lb_m$

(

FLIP UP MECHANISM

GENERAL FORM OF TORQUE EQUATION:

$$M_A = m_{TOT} g \frac{L}{2} \cos\theta + \frac{1}{3} m L^2 \alpha$$

GIVEN:

$m_{TOT} = 3.723 \, lbm$ (AL)

$m_{TOT} = 4.6766 \, lbm$ (ABS)

$L = 12 in = 1 ft$

$\alpha = 0.094 \, rad/s^2$

$g = 32.2 \, ft/s^2$

FOR ALL ALUMINUM:

$$M_A = (3.723 \, lb_m)\left(\frac{1 \, lb_f}{lb_m \cdot 32.2 ft/s^2}\right)(32.2 ft/s^2)\frac{1 ft}{2}\cos\theta + \frac{1}{3}(3.723 \, lb_m)\left(\frac{1 \, lb_f}{lb_m 32.2 ft/s^2}\right)(1 ft)^2(0.094 \, rad/s^2)$$

$$M_A = [1.8615\cos\theta + 0.00362] \, lb_f \cdot ft$$

FOR $\theta = 0°$

$M_A = 1.861512 \, lb_f \cdot ft \Rightarrow M_A = 22.38 \, lb_f \cdot in$

FOR $\theta = 90°$

$M_A = 0.00362 \, lb_f \cdot ft \Rightarrow M_A = 0.0434 \, lb_f \cdot in$

FOR $\theta = 180°$:

$M_A = -1.85788 \, lb_f \cdot ft \Rightarrow M_A = -22.29 \, lb_f \cdot in$

FOR $\theta = 270°$:

$M_A = 0.00362 \, lb_f \cdot ft \Rightarrow M_A = 0.0434 \, lb_f \cdot in$

FOR ABS:

$$M_A = (4.676 \, lb_m)\left(\frac{1 \, lb_f}{lb_m \cdot 32.2 ft/s^2}\right)(32.2 ft/s^2)\left(\frac{1 ft}{2}\right)\cos\theta + \frac{1}{3}(4.676 \, lb_m)\left(\frac{1 \, lb_f}{lb_m 32.2 ft/s^2}\right)(1 ft)^2(0.094 \, rad/s^2)$$

$$M_A = [2.338\cos\theta + 0.00455] \, lb_f \cdot ft$$

FOR $\theta = 0°$:

$M_A = 2.34255 \, lb_f \cdot ft \Rightarrow M_A = 28.11 \, lb_f \cdot in$

FOR $\theta = 90°$:

$M_A = 0.00455 \, lb_f \cdot ft \Rightarrow M_A = 0.0546 \, lb_f \cdot in$

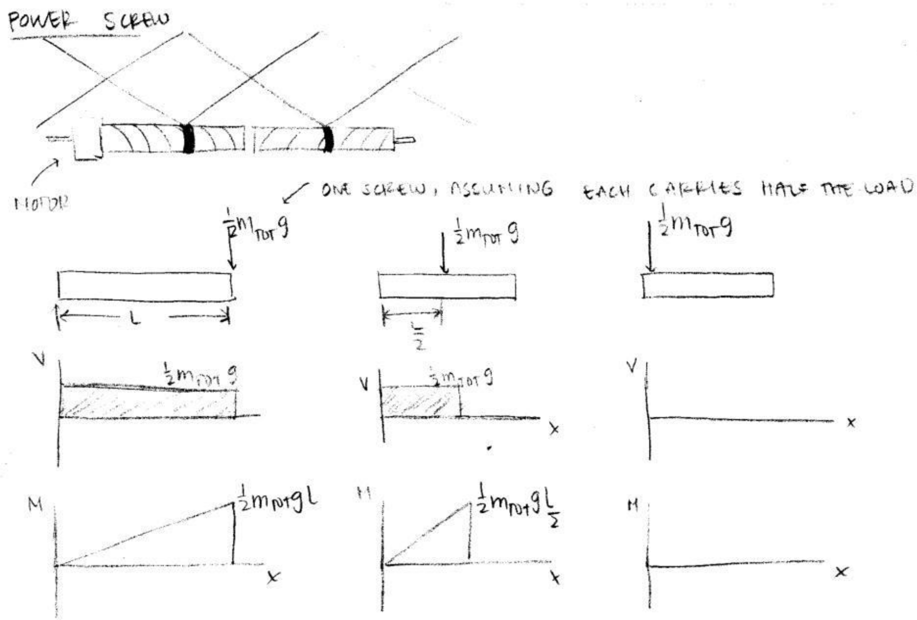
FOR $\theta = 180°$:

$M_A = -2.33345 \, lb_f \cdot ft \Rightarrow M_A = -28.00 \, lb_f \cdot in$

FOR $\theta = 270°$:

$M_A = 0.00455 \, lb_f \cdot ft \Rightarrow M_A = 0.0546 \, lb_f \cdot in$

(



$M_{max} = \frac{1}{2} m_{TOT}\, g L$

$M_{min} = 0$

USING 1019 MILD STEEL (LOW CARBON)

$S_{ut} = 63{,}800\,psi$

$S_y = 53{,}700\,psi$

USING DE MODIFIED GOODMAN FAILURE CRITERIA (FROM SHIGLEY'S) THE MINIMUM DIAMETER REQUIRED FOR THE POWER SCREW IS.

$$d = \left(\frac{16n}{\pi} \left\{ \frac{1}{S_e} \left[4(k_f M_a)^2 + 3(k_{fs} T_a)^2 \right]^{1/2} + \frac{1}{S_{ut}} \left[4(k_f M_m)^2 + 3(k_{fs} T_m)^2 \right]^{1/2} \right\} \right)^{1/3}$$

(

POWER SCREW
FROM SHIGLEY'S CH.6

1018 MILD STEEL
$S_{ut} = 63.8 \text{ kpsi}$

$S_e = k_a k_b k_c k_d k_e k_f S_e'$

$S_e' = 0.5 S_{ut} \Rightarrow S_{ut} \leq 200 \text{ kpsi}$

$S_e' = 0.5(63.8 \times 10^3 \text{ psi})$

$S_e' = 31.9 \times 10^3 \text{ psi}$

$k_a = a S_{ut}^b$

→ ASSUMING MACHINED OR COLD DRAWN

$a = 2.70, \quad b = -0.265$

$k_a = 2.70(63{,}800 \text{ psi})^{-0.265}$

$k_a = 0.144$

→ ASSUMING DIAMETER IS LESS THAN 2in

$k_b = (d/0.3)^{-0.107} = 0.879 d^{-0.107}$ FOR $0.11 \leq d \leq 2 \text{in}$

→ ASSUMING A DIAMETER OF $d = 0.188 \text{in}$

$k_b = 0.879(0.188 \text{in})^{-0.107}$

$k_b = 1.051$

→ ASSUMING FATIGUE TEST IS CARRIED OUT WITH ROTATING BENDING

$k_c = 1$

→ ASSUMING OPERATING TEMPERATURE IS 70°F OR LESS

$k_d = 1$

→ FOR 99% RELIABILITY.

$k_e = 1 - 0.08 z_a, \quad z_a = 2.326$

$k_e = 0.814$

→ ASSUMING NO MISCELLANEOUS-EFFECTS

$k_f = 1$

$S_e = (0.144)(1.051)(1)(1)(0.814)(1)(31.9 \times 10^3 \text{ psi})$

$S_e = 3926.15 \text{ psi}$

POWER SCREW

$\sigma_{max} = k_f \sigma_0$

ASSUMING SAE 5 SCREW WITH ROLLED THREADS

SIZE RANGE: $\frac{1}{4} - 1$ in

ENDURANCE STRENGTH: 186 kpsi

} TABLE 8-17 SHIGLEY'S

FROM TABLE 8-16

$k_f = 3.0$

$\sigma_0 = \frac{32M}{\pi d^3}$

$\sigma_{max} = 3.0 \left[\frac{32M}{\pi d^3} \right]$

$= 3.0 \left[\frac{32 \left(\frac{1}{2} m_{TOT} g L \right)}{\pi d^3} \right]$

ALUMINUM (ASSUMING WE'RE USING 2 SCREWS OF LENGTH $L = \frac{11}{2}$ in)

$M = \frac{1}{2} (3.723\ lb_m) \left(\frac{1\ lbf}{1 lb_m \cdot 32.2 ft/s^2} \right) (32.2 ft/s^2) \left(\frac{11}{2} in \right)$

$M = 10.24\ lb_f\ in$

ASSUMING $F_{min} = 0$.

$F_{max} = \frac{1}{2} m_{TOT} g$

$F_{min} = 0$

$F_m = \frac{F_{max} + F_{min}}{2}$ $\qquad F_a = \frac{|F_{max} - F_{min}|}{2}$

$F_m = \frac{F_{max}}{2}$ $\qquad F_a = \frac{F_{max}}{2}$

$F_m = F_a$

$\sigma_m = \frac{k_f F_m}{A} = k_f \frac{32 M_m}{\pi d^3}$ $\qquad \sigma_a = \frac{k_f F_a}{A} = k_f \frac{32 M_a}{\pi d^3}$

$M_m = \frac{F_m \pi d^3}{32A}$ $\qquad M_a = \frac{F_a \pi d^3}{32A}$

$F_m = F_a$ }

$M_m = M_a = \left(\frac{F_{max}}{2} \right) L = \frac{\frac{1}{2} m_{TOT} g}{2} \left(\frac{L_{TOT}}{2} \right) = \frac{1}{8} m_{TOT} g L_{TOT}$

$M_m = M_a = M = 5.119\ lb \cdot in$

POWER SCREW

USING A SAFETY FACTOR OF 5

$$d = \frac{16n}{\pi} \left\{ \frac{1}{S_e}\left[4(k_f M_a)^2 + 3(k_{fs} T_a)^2\right]^{1/2} + \frac{1}{S_{ut}}\left[4(k_f M_m)^2 + 3(k_{fs} T_m)^2\right]^{1/2} \right\}$$

$$d = \frac{16n}{\pi} \left\{ \frac{1}{S_e}\left[4(k_f M_a)^2\right]^{1/2} + \frac{1}{S_{ut}}\left[4(k_f M_m)^2\right]^{1/2} \right\}$$

$$d = \frac{16n}{\pi} \left\{ \frac{1}{S_e}\left[4(k_f M)^2\right]^{1/2} + \frac{1}{S_{ut}}\left[4(k_f M)^2\right]^{1/2} \right\}$$

$$d = \frac{16(5)}{\pi} \left\{ \frac{1}{3926.15}\left[4(3 \times 5.119)^2\right]^{1/2} + \frac{1}{63{,}800}\left[4(3 \times 5.119)^2\right]^{1/2} \right\}$$

$d = 0.2114$ in ← GO BACK TO EXCEL TO ITERATE

TORQUE NEEDED FROM EACH SCREW TO MOVE THE LOAD UP AND DOWN

RAISING LOAD:

$L = 0.05$

$f = 0.61$ (Al-Steel)

$$T_R = \frac{F d_m}{2}\left(\frac{L + \pi f d_m}{\pi d_m - fL}\right)$$

$$= \frac{\frac{1}{2}(3.723\,lbf)(0.2114\,in)}{2}\left[\frac{0.05\,in + \pi(0.61)(0.2114\,in)}{\pi(0.141\,in) - 0.61(0.05\,in)}\right]$$

$T_R = 0.1527$ lbf in

LOWERING LOAD:

$$T_L = \frac{F d_m}{2}\left(\frac{\pi f d_m - L}{\pi d_m + fL}\right)$$

$$= \frac{\frac{1}{2}(3.723\,lbf)(0.2114)}{2}\left[\frac{\pi(0.61)(0.2114) - 0.05}{\pi(0.2114\,in) + 0.61(0.05\,in)}\right]$$

$T_L = 0.0915$ lbf in

POWER SCREW:

FORCE NEEDED TO RAISE LOAD

$$P_R = \frac{F\left[(l/\pi d_m) + f\right]}{1 - (fl/\pi d_m)}$$

$$= \frac{3.723\,lbf\left[\left(\frac{0.05in}{\pi(0.2114in)}\right) + 0.61\right]}{1 - \left[\frac{0.61(0.05in)}{\pi(0.2114in)}\right]}$$

$$P_R = 4.62\ lb_f$$

FOR LOWERING THE LOAD

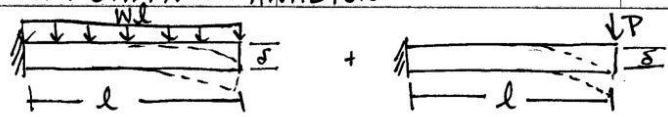
$$P_L = \frac{F\left[f - (l/\pi d_m)\right]}{1 + (fl/\pi d_m)}$$

$$= \frac{3.723\,lb_f\left[0.61 - \left(\frac{0.05in}{\pi(0.2114in)}\right)\right]}{1 + \left[\frac{0.61(0.05in)}{\pi(0.2114in)}\right]}$$

$$P_L = 1.903\ lb_f$$

(

GRATING STIFFNESS ANALYSIS



$$\delta = \frac{WL^4}{8EI} \quad + \quad \delta = \frac{PL^3}{3EI}$$

$$\boxed{\delta_T = \frac{L^3(3WL + 8P)}{24EI}}$$

$L = 12\,in$

$I = \frac{1}{12} bh^3$

$b = 1.5\,in$

$\delta_{max} = 0.016\,in$

$W = 10 * $ BEAM WEIGHT

$W = 10 \gamma V$

$\gamma_{ABS} = 0.0376\ lb/in^3$, $\gamma_{AL} = 0.098\ lb/in^3$

$V = bLt$

$= (1.5in)(12in)t$

$= 18t$

$W_{ABS} = (10)(0.0376\ \frac{lb}{in^3})(18t) = 6.768t\ [lb/in]$

$W_{AL} = (10)(0.098\ lb/in^3)(18t) = 17.64t\ [lb/in]$

DISTRIBUTED WEIGHT → W/L

$\frac{W}{L}_{ABS} = 0.564t\ \frac{lb}{in^2}$ | $\frac{W}{L}_{AL} = 1.47\ \frac{lb}{in^2}$

WEIGHT OF SCISSORS + GUIDE RAIL

$P_{AL} = 0.4515\ lb$ | $P_{ABS} = 0.173\ lb$

↳ SOLVE FOR t:

$$t^3 = \frac{3600[36W + 8P]}{E}$$

FOR ALL ABS PLASTIC

$W = 0.564t \quad P = 0.173 \quad E = 2\times10^5$

$$t^3 = \frac{3600[36(.564t) + 8(.173)]}{2\times10^5}$$

$\boxed{t = 0.638\,in}$

FOR ALL ALUMINUM

$W = 1.47 \quad P = 0.4515 \quad E = 10\times10^6$

$$t^3 = \frac{3600[36(1.47t) + 8(.4515)]}{10\times10^6}$$

$\boxed{t = 0.16\,in}$

FOR PLASTIC BEAMS & ALUMINUM SCISSORS/GUIDE RAILS

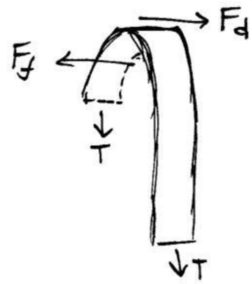
$W = 0.564t \quad P = 0.4515 \quad E = 2\times10^5$

$$t^3 = \frac{3600[36(0.564t) + 8(.4515)]}{2\times10^5}$$

$\boxed{t = 0.68\,in}$

BELT TENSION ANALYSIS

* THIS IS THE MOST SIMPLIFIED FORM

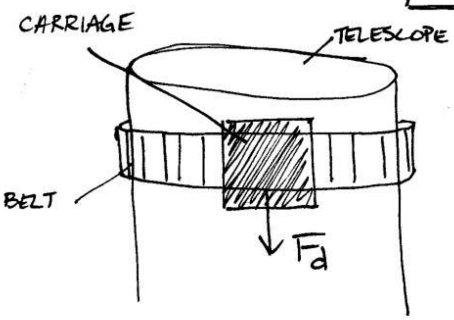


$$N = 2T$$

$$F_d = F_f$$
$$= \mu N$$
$$= \mu(2T)$$

$$\boxed{T = \frac{F_d}{2\mu}}$$

$\mu = 1.16$ FOR RUBBER



WORST CASE SCENERIO

TOTAL WEIGHT
- SCISSORS X2
- GUIDE RAIL X2
- GRATING × 10
= 3.7254

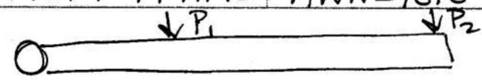
ASSUME: $W_{CARRIAGE} = W_{GRATING}$

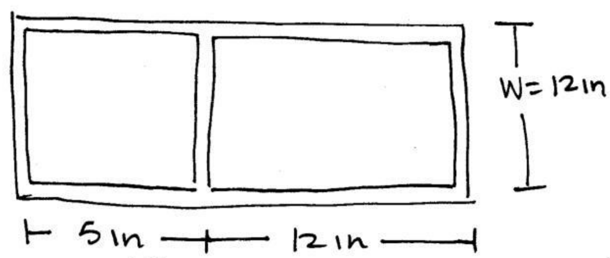
$$W_{GRATING} = 2P_{AL} + W_{AL} = 2(.4515) + 2.8224$$
$$= 3.7254 \text{ lb}$$

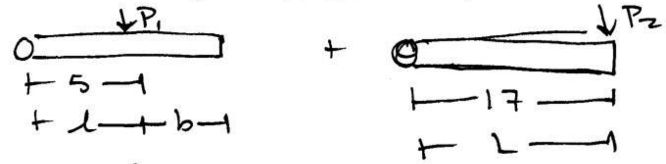
$$F_d = W_{GRATING} + W_{CARRIAGE}$$
$$= (3.7254)2 = 7.45 \text{ lb}$$

$$T_{REQUIRED} = \frac{(7.45 \text{ lb})}{2(1.16)} = \boxed{3.2 \text{ lb}}$$

SUPPORT FRAME ANALYSIS







$$\delta = \frac{P_1 l^2}{6EI}(2l+3b) \qquad \delta = \frac{P_2 L^3}{3EI}\left(\frac{2}{2}\right)$$

TO GET COMMON DENOMINATOR

$$\delta_{TOT} = \frac{2P_2L^3 + P_1 l^2(2l+3b)}{6EI}$$

$$I = \frac{2(0.22575)(17)^3 + (0.22575)(5^2)(2(5)+3(12))}{6(10\times10^6)(0.016)}$$

$$I = 0.00258\,in^4$$

*SAFETY FACTOR OF 5

$$I = 0.012905\,in^4 = \frac{1}{12}bt^3$$

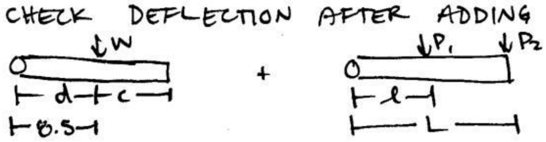
$$t^3 = \sqrt[3]{\frac{0.15486}{b}}$$

KNOWN VARIABLES

- $\delta_{TOT} = 0.016in$
- $L = 17in$
- $l = 5in$
- $E = 10\times10^6\,psi$
- $P_2 = P_1 = \frac{1}{2}$ OF THE SHARED WEIGHT OF THE SCISSORS AND GUIDE RAILS $= 0.22575lb$

→ USING EXCEL, BEST DIMENSIONS ARE ½" x ½"

→ CHECK DEFLECTION AFTER ADDING WEIGHT OF FRAME



$$\delta = \frac{Wd^2(2d+3c) + 2P_2L^3 + P_1 l^2(2l+3b)}{6EI}$$

$$\delta = 0.012in < 0.016in$$ ✓

DESIGN ANAL: GRATING 12/4/2014

PRECISION ACTUATORS

(KELLY HAS PRIMARY RECORDS)

DEC 21ST MTG.

MATERIAL RESEARCH: ALL.
COMPARE UPON RETURN.
TIM: MASTER CHART.

FLEX ANALASYS

RAM: BELTS. ← EMAIL ← L/o.
SANTOS
BELL-EVERMAN.

HOW SMALL ACT HOW HIGH A STRESS
LIN ACT.

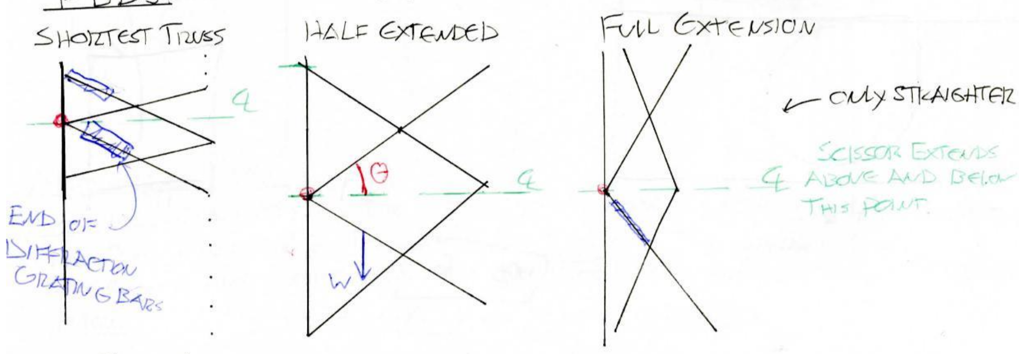
FLEX ANALLSYS OF THE SCISSOR MECHANISM. 12/20/2014

ASSUMPTIONS: THE USUAL ASSUMPTIONS FOR SIMPLEFYING/ANALIZING THIS SORT OF SYSTEM HAVE BEEN MADE. NAMELY:

- CONTINUOUS MATERIALS
- UNIFORM ~~SF~~ LOADS/ POINT LOADS (SEE SKETCHES)
- STATIC EQUILIBRIUM (VERIFY IF DYNAMIC IS NEEDED LATER)
- SIMPLE TRUSS (2-FORCE MEMBERS?)

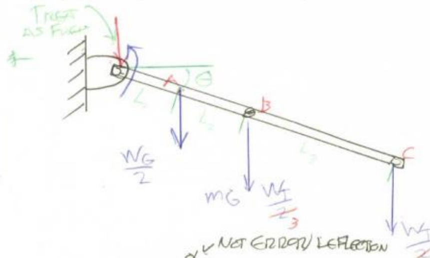
GOAL: TO DERIVE EQUATIONS FOR DETERMINING THE AMMOUNT OF FLEX IN THE SCISSOR MECHANISM.

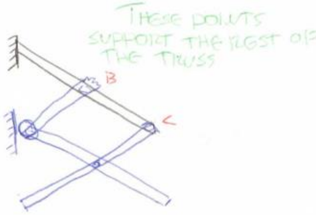
FBDS + SKETCHES.



IF TENSILE LOADING IS CONSIDERED TO BE NEGLIGABLE, BEAM BENDING IS DOMINANT, AND THE SHORTEST IS CRITICAL. 25

SINCE ONLY ONE TRUSS LINKAGE IS ATTACHED TO THE MOTOR IN THIS DESIGN, THE "PRIMARY" LINKAGE WILL BEAR THE ENTIRE LOAD OF THE TRUSS, AND WILL BE THE MOST STRESSED.





NOT ERROR/ DEFLECTION

$\delta y_a = L_1 \sin\theta + -\frac{W_G L^3}{2(3EI)} - \frac{M_A L^2}{2EI}$ $M_A = (mg + \frac{W_T}{2})L_2 + \frac{W_T}{2}(L_2 + L_3)$

ASSUME $\phi \cong \alpha$?

$\phi_L =$

IS SLOPE INSIGNIFICANT?

$\delta y_B = \delta y_a + (L_1 + L_2)\sin\theta + -\frac{(MG + \frac{W_T}{2})(L_1 + L_2)^3}{6EI} - \frac{M_B L^2}{2EI}$ $M_B = L_3 \frac{W_T}{2}$

$\delta y_c = \delta y_B + (L_1 + L_2 + L_3)\sin\theta - \frac{W_T}{2}\frac{(L_3 + L_2 + L_1)^3}{(3EI)}$

- NEXT: ANAL USING ALUMINUM
  - FIND BASIC GEOM
  - FIND DEFLECTION OF MULTIPLE BARS

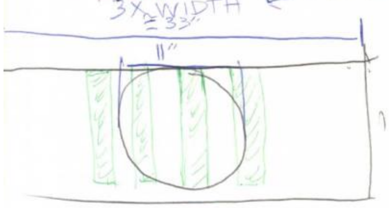
1/2/2015

GEOMETRIC ANAL:

FRONT

3X WIDTH ← MAX WIDTH

≅ 33"



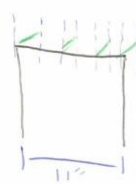
- BARS WIDEST
- 3-4 BARS MINIMUM

IF WE START W/
~4 BARS
3 GAPS
11 IN COVER
10° MIN
↳ BAR WIDTH =

$\frac{11''}{7} \times \frac{1}{\cos 10°} = 1.60$

≅ 1.5

SIDE

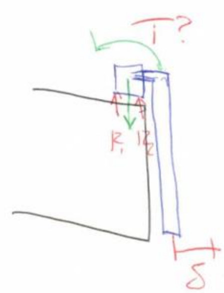


SR. PROJECT LECTU

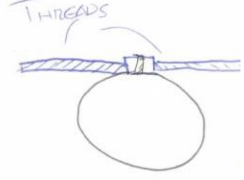
CDR IN 5 WEEKS

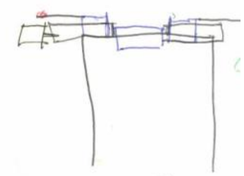
LONG LEAD ITEMS

USE SIMPLE MO



SCREW DESIG





ALLOWABLE FLEX: S

ASSUME: CURRENTLY

THAT THE ALLOWABLE

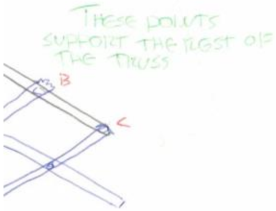
SINCE WE ARE WO

SOLUTION: 1.6" x .01

DOES NOT INCLUD

26

…HED TO THE MOTOR
… BEAR THE ENTIRE
…T STRESSED.



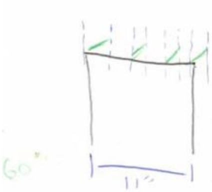
$(mg+\frac{W_T}{2})L_2 + \frac{W_T}{2}(L_2+L_3)$

$\ldots^3 - \frac{M_B L^2}{2EI}$ $M_B = L_3 \frac{W_T}{2}$

3

1/2/2015

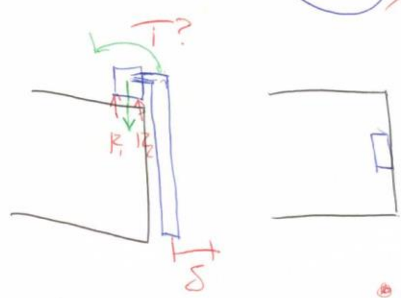
SIDE



SR. PROJECT LECTURE 1/6/2015

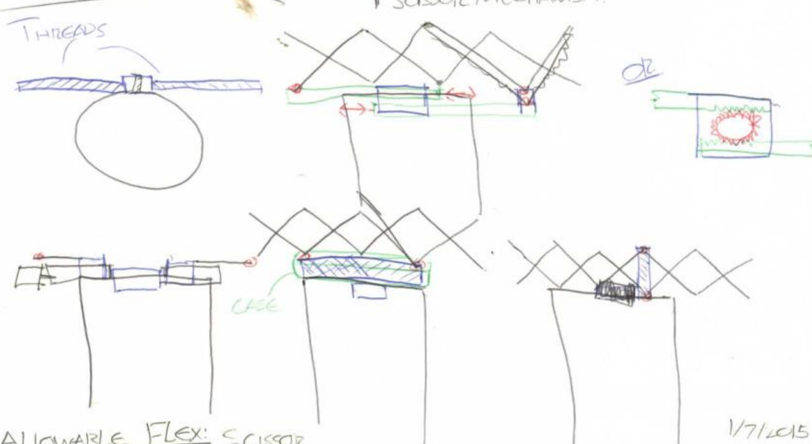
CDR IN 5 WEEKS
LONG LEAD ITEMS BY 1/9
USE SIMPLE MODELS FOR PURCHASED COMPONENTS

1/6/2015



SCREW DESIGN 1/6/2015

ATTACH POINTS
THREADED BOLT/RAIL
SCISSOR MECHANISM



ALLOWABLE FLEX: SCISSOR 1/7/2015

ASSUME: CURRENTLY BY DR. RIDGELY'S RECOMMENDATION WE ARE ASSUMING THAT THE ALLOWABLE TOLERANCE IS ± 1% OF THE OVERALL GAP. SINCE WE ARE WORKING WITH AN ASSUMED GAP OF 1.6"

SOLUTION: 1.6" x .01 = .016" ← MAX δ OF SCISSOR

DOES NOT INCLUDE CANTILEVER δ FROM BARS.

1/7/2015

— WE WILL ACCOUNT

HIS SIMPLY GIVES US.

max = 0.016"?

IFICANT.

1/8/2015

SCREW DESIGN

ENARIO IS THE MOST

THE TRUSS WILL BE

S HANGING FREE.

THIS

1/9/2015

1/10/2015

G THE CARRIAGE IS

R = M

= 8 lbf?

OUT HOW TENSION

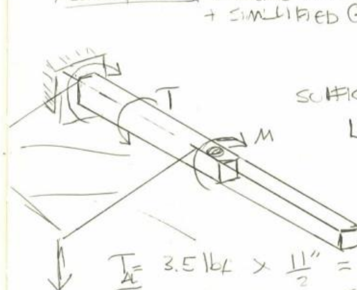
O NORMAL FORCE

SCISSOR LINKAGE TWIST ANAL

1/12/15

1/13/2015

ASSUMPTIONS! ASSUME WORST CASE SCENARIO + SIMPLIFIED GEOMETRY



1. ASSUME SECOND PIN CAN SUPPLY MOMENT SUFFICIENT TO "FIX"

↳ BY SYMMETRY:

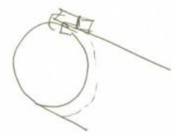
USE: W = 3.5 lbf ← ALUMINUM?

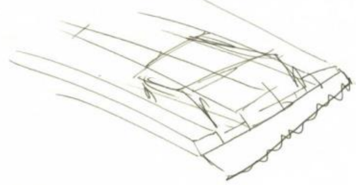
W = 1.25 lbf ← ABS?

$T_{Al} = 3.5\ lbf \times \frac{11"}{2} = 19.25\ lb\cdot in$

$T_{ABS} = 1.25 \times 5.5" = 6.875\ lb\cdot in$

1/14/2015





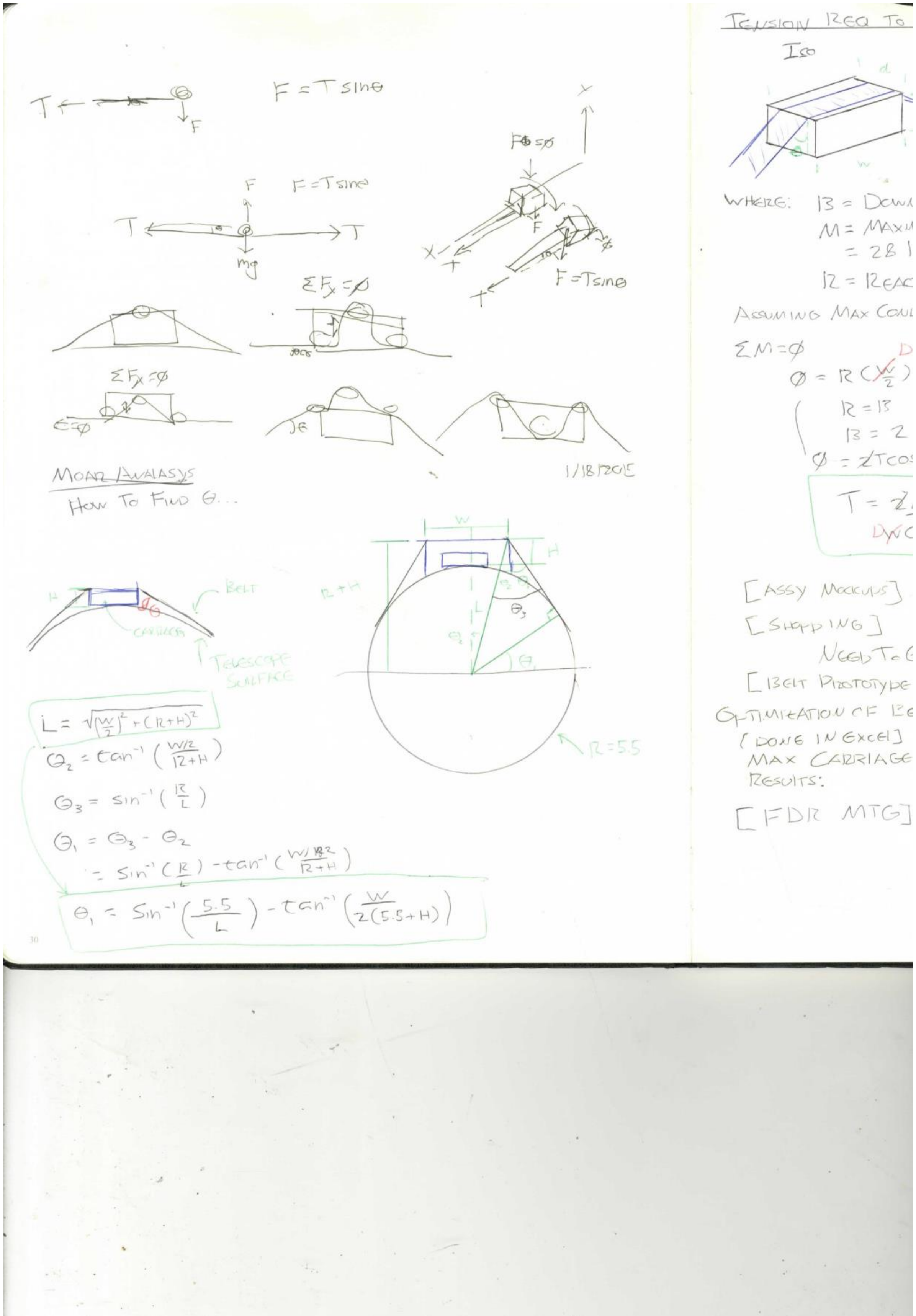
[BELT SHOPPING]

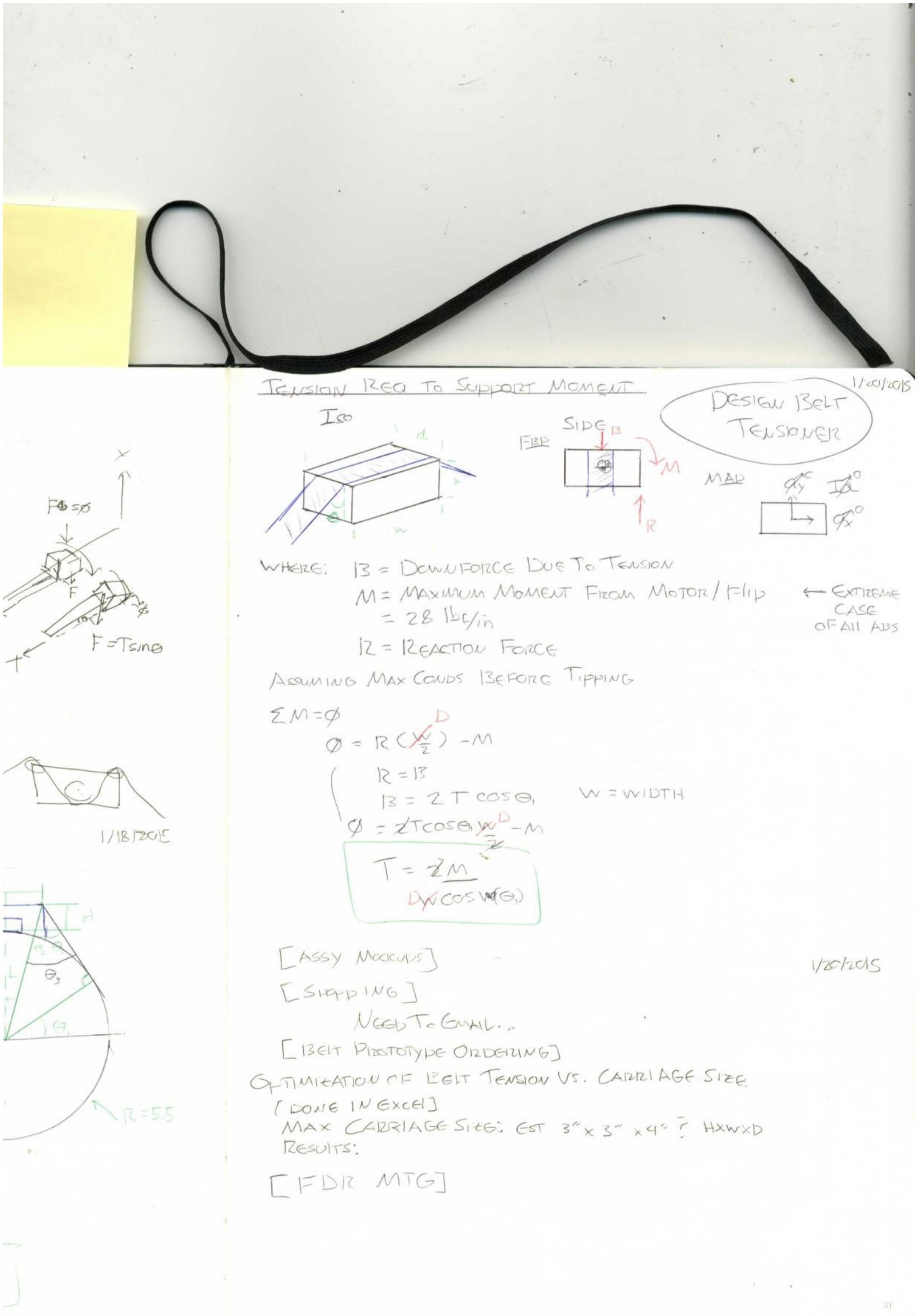
1/14/2015

MORE CARRIAGE ANAL.

FROM PREV: NORMAL FORCE = 8 lbf

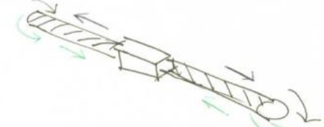
← 90° WONT WORK, INTERNAL FORCES CANCEL? FOR THAT MATTER WILL ANY?


F = T sinθ
F = T sinθ
ΣFx = Ø
ΣFx = Ø
1/18/2015
MOAR ANALYSYS
How To Find θ...
BELT
CARRIAGE
TELESCOPE SURFACE
R = 5.5
L = √((W/2)² + (R+H)²)
θ2 = tan⁻¹ (W/2 / R+H)
θ3 = sin⁻¹ (R / L)
θ1 = θ3 − θ2
θ1 = Sin⁻¹ (5.5 / L) − tan⁻¹ (W / 2(5.5+H))
TENSION REQ TO
ISO
WHERE:
ASSUMING MAX CONT
ΣM = Ø
[ASSY MOCKUPS]
[SHOPPING]
[BELT PROTOTYPE
OPTIMIZATION OF BE
[DONE IN EXCEL]
MAX CARRIAGE
RESULTS:
[FDR MTG]


TENSION REQ TO SUPPORT MOMENT
1/20/2015
DESIGN BELT TENSIONER
ISO
SIDE
FBD
M
R
MAP
WHERE: B = DOWNFORCE DUE TO TENSION
M = MAXIMUM MOMENT FROM MOTOR / FLIP
= 28 lbf/in
R = REACTION FORCE
← EXTREME CASE OF ALL ABS
ASSUMING MAX CONDS BEFORE TIPPING
ΣM = 0
0 = R(D/2) - M
R = B
B = 2T cos θ
W = WIDTH
0 = 2T cos θ D/2 - M
T = 2M / D cos(θ)
[ASSY MOCKUPS]
1/20/2015
[SHIPPING]
NEED TO EMAIL..
[BELT PROTOTYPE ORDERING]
OPTIMIZATION OF BELT TENSION VS. CARRIAGE SIZE
[DONE IN EXCEL]
MAX CARRIAGE SIZE: EST 3" x 3" x 4" ? HxWxD
RESULTS:
[FDR MTG]
F = T sin θ
1/18/2015
R = 5.5

SCREW:

SCREWS MUST BE OPPOSITE THREADED



SAMPLE CALC FOR TENSION: ✓ = match Nick Sideways Tension?

LET ~~H = 3", W = 3", D = 4"~~ 1/22/2015

H = 4", W = 4", D = 5" ← WANT TO USE THESE #s.

$L = \left(\left(\frac{4}{2}\right)^2 + (5.5+4)^2 \right)^{\frac{1}{2}}$

$= 9.0708$ in ✓

$\Theta_1 = \sin^{-1}\left(\frac{5.5}{9.708}\right) - \tan^{-1}\left(\frac{4}{2(5.5+4)}\right)$

$= 22.62$ ✓

$T = \frac{M}{D\cos\Theta_1}$

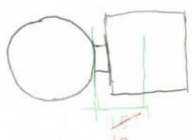
$= \frac{(28 \text{ lbf in})}{5\cos(22.62)}$

$= 6.067$ ✓ Req Belt Tension Due To ⊥ Loading

1/22/2015

WHAT IF IT'S SIDEWAYS?

$M = M_{6"}\left(\frac{10"}{6"}\right) = 46.67"$

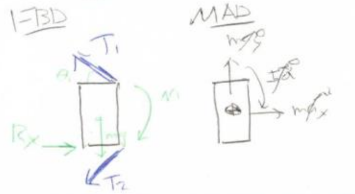


$\Sigma M = 0$

$\emptyset = T(W/2)\cos\Theta + R_x \frac{W}{2} - M$

$R_x = T\cos\Theta_1 + \frac{T}{2}\cos\Theta_2 - \frac{T}{2}(W/2)\cos\Theta_1$

FBD MAD



$\emptyset = T_1 W\cos\Theta_1 - M$

$T = \frac{M}{W\cos\Theta_1}$

cont...

$\Sigma F_y = \emptyset$

$\emptyset = T_1\sin\Theta_1$ -

↳ Tension R

- Buckle Sketch

Bracket Layout

Scissor Size Re-

Total Weight W_T

$S_{ymax} = S_{yB} + -\frac{W_T}{2}(\Sigma$

$= -\frac{W_T}{2}\frac{(\Sigma L)^3}{3EI}$

$I = \left(-\frac{W_T}{2}\left(\frac{(\Sigma L)^3}{3EI}\right) + \right.$

$= (-7.53375(9E$

$= -1.491\times10^{-6}$

For Square: $I = \frac{1}{12}$

↳ $b = ($

ETHREADED

Sideways Tension?

1/22/2015

o use these #s

To ⊥ Loading

1/22/2015

.67"

$\cos\theta + R_x \frac{W}{2} - M$

$= T_1\cos\theta_1 + T_2\cos\theta_2$

$\cdot T_2(W/2)\cos\theta_1$

$\cos\theta_1 \ast -M$

$\cos\theta_1$

cont...

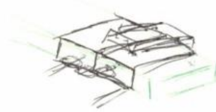
$\Sigma F_y = \emptyset$

$\emptyset = T_1 \sin\theta_1 - mg - T_2 \sin\theta_2$ or in theory?

↳ Tension Req for Sideways = 12.6 lbs

1/23/2015

- Buckle Sketches



[FDR] 1/24/2015

[Layout Sketches] 1/24/2015

[Part Searches] 1/24/2015

Bracket Layout

1/25/2015

Scissor Size Re-Eval

Total Weight $W_T = W_s \times 40 + .5075 = 15.0675$ lb (3675)

$W_s = 0.3675$ lb/bar $W_{s+} =$

$W_{B+} = 0.5075$ lb (4230)

$L_3 = 1.5"$

$L_T = 3$

$E = 10 \times 10^6$

$L_4 = .75" = L_2 = L_3$

$\delta_{ymax} = \delta_{yB} + -\frac{W_T}{2}\frac{(\Sigma L)^3}{3EI}$

$M_A = (W_s + \frac{W_T}{2})L_2 + \frac{W_T}{2}(L_2+L_3)$

$= -\frac{W_T}{2}\frac{(\Sigma L)^3}{3EI} - W_B + \frac{\frac{W_4}{2}(L_1+L_2)^3}{6EI} - \frac{L_3 W_T}{2} - \frac{W_B L_1^3}{2(3EI)} - \frac{M_A L^2}{2EI}$

$I = \left(-\frac{W_T}{2}\left(\frac{(\Sigma L)^2}{3E} + \frac{(L_1+L_2)^3}{6E}\right) - \frac{W_B L_1^3}{6E} - \frac{M_A L^2}{2E}\right) / \left(+W_b + L_3\frac{W_4}{2} + .015\right)$

$= (-7.53375(9E^{-7} + 5.625E^{-8}) - 2.974E^{-9} - 1.029E^{-5}) / (11.7386)$

$= -1.491 \times 10^{-6}$ in²

For Square: $I = \frac{1}{12} b^4$

↳ $b = (12 I)^{\frac{1}{4}}$ = .065 in

F.S. = 5

↳ B = .325"

Appendix E: Design Verification Plan and Report

ME428 DVP&R Format

Report Date		12/1/14	Sponsor	Dr. Genet	Dr. Ridgely				Component/Assembly			REPORTING ENGINEER:	Kelly R.
TEST PLAN										**TEST REPORT**			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsib	Test Stage	SAMPLES Quantity	Type	TIMING Start date	Finish date	TEST RESULTS Test Result	Quantity Pass	Quantity Fail	NOTES
1	1 - Angular Accuracy 3 - Rotation	Compare the input angular position with the actual position that the system reaches. Test a large variety of positions	Should be able to rotate 360° Position must not vary more than 0.1°	Kelly	DV	1		4/16/14	4/23/14				
2	2 - Weight	Mount the device onto the telescope and check to see if it negatively affects the movement of the telescope	Should not affect the functionality of the telescope	Edlin	DV	1		4/23/14	4/30/14				
3	4 - Speed	Time the system to see how long it takes for it to change diffraction patterns	Should be able to change diffraction pattern in less than 10 seconds	Tim	DV	1		4/30/14	5/8/14				
4	7 - Adjustability of Bar/Gap Width	Test to see if the grating can change periods. Check to see if it reaches the maximum and minimum lengths	Should be able to adjust to a 1:3 ratio	Kelly	DV	1		4/2/14	4/16/14				
5	8 - Diffraction Functionality	Use the ADS simulator to check if our diffraction gratings obtain the desired patterns	Should produce desired patterns from ADS Simulator	Edlin	DV	1		1/6/14	1/20/14				
6	10 - Mounting	Mount the device onto the telescope and check for stability	Should fit a 10-11in Telescope Diameter	Tim	DV	1		4/23/14	4/30/14				
7	11 - Environmental Conditions	Put the device in variatious temperaures and environmental conditions for a period of time and see how it is affected	Should be able to withstand 0-50°C, fog, and corrosion	Kelly	DV	1		5/8/14	5/19/14				
8	15 - Optical Quality of Transmission	Test the diffraction pattern of known binary star systems and see if we obtain the correct pattern for the star's wavelength	Incoming light should not refract more than 1/10 of its wavelength	Edlin	DV	1		1/20/14	2/3/14				
9													
10													
11													
12													
15													
16													
17													
18													
19													
20													
21													
22													
23													
24													
25													
26													
27													
28													
29													
30													

Appendix F: Automatic Diffraction Grating User Manual

Team StarT.E.K.

Tim Jung – Edlin Garcia – Kelly Rorden

Preface

This user's guide is written as a companion to the Automatic Diffraction Grating. It summarizes the installation, basic mechanical features, and software commands required for basic use of the system. This document is not intended to be a complete guide of the design or assembly of the Automatic Diffraction Grating; this information can be found in the Final Project Report for the project.

Disclaimer

Table of Contents

Installation

The Automatic Diffraction Grating is designed to be mountable to various sizes of telescope, but is optimized for use with 11" telescopes.

There are three steps to installing the Automatic Diffraction Grating onto a telescope. First, the protective sleeve and guide rail is strapped to the telescope. Second, the carriage is positioned on the sleeve. Finally, the drive chains are hooked onto the positioning buckle.

Power and USB will also need to be connected in order for this to be used.

Step 1: Mounting the Sleeve

Take the black neoprene and elastic sleeve and place it over the telescope with the rails and steel plate pointed out away from the telescope. Slide the sleeve down as needed so that the shorter of the two rails is flush with the objective end of the telescope.

Hook the ends of the springs into the holes on the ends of the rails. Make sure that the rails are properly tensioned around the telescope, and that the sleeve is flat against the telescope.

Step 2: Position the Carriage

Place the carriage on the sleeve so that the diffraction grating hangs over the front of the telescope. Allow the magnets to attach the carriage to the sleeve, and ensure that the carriage is firmly seated.

Make sure that the magnets on the bottom of the carriage do not contact the steel strip. If they do, the carriage may not rotate as freely as desired.

Step 3: Fasten the Chains

Wrap the chains around the telescope, and hook them onto the buckle. Make sure that the chains are evenly spaced and tensioned.

Step 4: Connect Power and USB

Plug the Power cable into a standard 120V AC wall outlet.

Plug the USB cable into the laptop that will be driving the Automatic Diffraction Grating.

Software Commands

While the end goal for the Automatic Diffraction Grating is for it to be able to communicate with standard astronomical software, the current software implementation is a simple set of commands that allow the Grating to be controlled remotely via USB. This list of commands is not case sensitive.This list of commands is summarized below.

A – Puts the Diffraction Grating in Auto Mode

Currently the Auto mode is programmed to simply cycle the position of the scissor and angle by 100 ticks.

X or O – Puts the Diffraction Grating in Manual Mode

Cancels the Automatic Mode and allows the diffraction grating to be controlled using entered commands.

S[#] - Move the Scissors

Typing the letter “S” followed by a number instructs the grating to move that number of ticks.

- Positive numbers widen the grating. E.g. S100 will move the grating open 100 ticks.
- Negative numbers close the grating. E.g. S-250 will close the grating 250 ticks.

R[#] – Rotate the Diffraction Grating

Typing the letter “R” followed by a number instructs the grating to rotate that number of ticks.

- Positive numbers will rotate the grating clockwise. E.g. R100 will rotate the grating clockwise 100 ticks.
- Negative numbers will rotate the grating counterclockwise. E.g. R-300 will rotate the grating counterclockwise 300 ticks.

Troubleshooting

Below are a few troubleshooting options for potential issues with the Automatic Diffraction Grating.

Issue: Carriage will not Move

- Make sure that the Carriage is properly aligned.
- Ensure that the magnets on the bottom of the carriage are not contacting the steel plate. This will cause high levels of friction.
- Ensure that the power leads are properly connected, and that power is turned on.

Issue: Scissors will not Move

- Ensure that the scissors are not at their limits.

Contacts

Project Sponsors: Dr. Russ Genet russmgenet@aol.com

Dr. John Ridgely jridgely@calpoly.edu

StrT.E.K. Liason: Tim Jung tim_jung@ymail.com

Appendix G: Code

Main Program

```
/* * * * * * * * * * * * * * * * * * * * * * *
/* Automatic_Diffraction_Grating.ino
/* Author: Tim Jung w/ Kelly Rorden and Edlin Garcia
/* Date Created: 4/26/2015
/* Last Edited: 5/27/2015
/*
/* This is the main program for running the Automatic Diffraction
/* Grating Sr. Project.
/*
/* This code is also sexy as hell.
/*
/* This project was sponsored by CP Connect, and conducted
/* at the request of Dr. Russ Genet and Dr. Ridgely.
/*
/* Special Thanks to advisor Dr. Peter Schuster
/* Special Thanks to Kelly Rorden and Edlin Garcia
/* * * * * * * * * * * * * * * * * * * * * * *
*/

#include <Encoder.h>
#include <motor.h>

/* * * * * * * * * * * * * * * * * * * * * * *
*/

//Motor Variables
int pinA = 13;
int pinB = 12;
int enable = 8;
int pwm_pin = 11;
int pwm = 0;
int count = 0;         //Stupid counter for the stupid co-op-multi <---
- Written after the rage comment below

int scissorSpeed = 100;
int carriageSpeed = 250;

//Enoder Variables
long positionLeft  = -999;
long positionRight = -999;

long desiredS = 0;
long desiredR = 0;

//Flags
bool auto_mode = false;

//States
int inputState = 1;
```

```
/* * * * * * * * * * * * * * * * * * * * * *
/*Initilize Objects
*/


motor Motor1(12, 13, 8, 11);      // Initilize Carriage Motor
motor Motor2(6, 7, 8, 5);          //Initilize Scissor Motor

// Change these pin numbers to the pins connected to your encoder.
//   Best Performance: both pins have interrupt capability
//   Good Performance: only the first pin has interrupt capability
//   Low Performance:  neither pin has interrupt capability
Encoder knobLeft(2, 9);
Encoder knobRight(3, 4);
//   avoid using pins with LEDs attached



/* * * * * * * * * * * * * * * * * * * * * *
/* Setup
*/

void setup() {
  // put your setup code here, to run once:   <-- Yes, Arduino is
wierd.

  //Initilize Serial and Print Startup Message
  Serial.begin(9600);
  Serial.println("Welcome to the Automatic Diffraction Grating
Project!");
  Serial.println("This program was written by Tim 'Longshot' Jung,
Kelly 'Kelltron' Rorden, and Edlin 'AcHoOoooO' Garcia");
  Serial.println("California Polytechnic State University");
  Serial.println("Yes we have blonds.");
  Serial.println("Yes we have brunetts.");
  Serial.println("We're not soo good at soccer.");

  // Initilize Motor 1
  Motor1.on();
  Motor1.power(0);
  Motor2.power(scissorSpeed);

}

/* * * * * * * * * * * * * * * * * * * * * *
/* Loop
*/

void loop() {
```

```
  // put your main code here, to run repeatedly:

  //FREAKING A I"M GOING TO HAVE TO CO-OPERATIVELY MULTITASK THIS
  // #$@!&$%@!!

  //Lets go for 1 second cycles in 10 ms increments
  //(Count goes 0-100 every 1 ms, then resets)

  count++;

  if (auto_mode)
  {
    testMotor();
    desiredS = positionLeft;
    desiredR = positionRight;
  }
  else
  {
    manualMotor();
  }

  getInput();

  testEncoder();

  //Reset Count if needed
  if (count >= 10000) //Every 5000*10 ms
  {
    count = 0;
  }

  delay(10);    //Should be 10 ms delay
}

/* - - - - - - - - - - - - - - - - - - - - - -
/* testMotor()
/*
/* A function to *wait for it* ...
/* Test the Motor!
/* Currently it goes back and forth every 5 seconds
/* - - - - - - - - - - - - - - - - - - - - - -
*/
void testMotor()
{
  if (count < 5000)
  {
    Motor1.forward();
    Motor2.forward();
  }
  else
  {
```

```
    Motor1.backward();
    Motor2.backward();
  }
}

/* - - - - - - - - - - - - - - - - - - - - -
/* testEncoder()
/*
/* A function to *wait for it* ...
/* Test the Encoder!
/* I didn't write this, it's public domain.
/* http://www.pjrc.com/teensy/td_libs_Encoder.html
/* - - - - - - - - - - - - - - - - - - - - -
*/

void testEncoder()
{
  long newLeft, newRight;
  newLeft = knobLeft.read();
  newRight = knobRight.read();
  if (newLeft != positionLeft || newRight != positionRight) {
    Serial.print("Scissor Position = ");
    Serial.print(newLeft);
    Serial.print(", Carriage Position = ");
    Serial.print(newRight);
    Serial.println();
    positionLeft = newLeft;
    positionRight = newRight;
  }

  /*
  // if a character is sent from the serial monitor,
  // reset both back to zero.
  if (Serial.available()) {
    Serial.read();
    Serial.println("Reset both knobs to zero");
    knobLeft.write(0);
    knobRight.write(0);
  }
  */
}


/* - - - - - - - - - - - - - - - - - - - - -
/* getInput)
/*
/* A function to *wait for it* ...
/* Retrieve and parse the user's input!
/* - - - - - - - - - - - - - - - - - - - - -
*/
void getInput()
```

```
{
  if(inputState == 1)
  {

      if (Serial.available())
      {

        //Get the command
        char command;
        double length = Serial.readBytesUntil(',', &command, 1);

        //Check the command
        switch (command)
        {
          case 'r':
          case 'R':
           // Serial.println("Updating Carriage Position");
          // desiredR = positionRight + Serial.parseInt();
            inputState = 3;
            break;

          case 's':
          case 'S':
          //  Serial.println("Updating Scissor Posiiton");
            inputState = 2;
            break;

          case 'a':
          case 'A':
            //     case 'run':
            Serial.println("Running Auto Mode...");
            auto_mode = true;
            Motor1.power(carriageSpeed);
            Motor2.power(scissorSpeed);
            break;
          case 'O':
          case 'o':
          //     case 'off':
          case 'x':
          case 'X':
            //    case 'stop':
            Serial.println("Auto Mode Stopped. Switching to Manual
Input");
            auto_mode = false;
            Motor1.power(0);
            Motor2.power(0);
            break;
          default:
            Serial.println("Unknown Command. ");
            break;
        }
```

```
      }
  }

  if (inputState == 2)
  {
  //  Serial.println("Enter Number:");
    if(Serial.available())
    {
      Serial.println("Updating Scissor Posiiton");
      desiredS = positionLeft + Serial.parseInt();
      Serial.println("Position Updated");
      Serial.print("Desired Position: ");
      Serial.print(desiredS);
      Serial.println();
      Serial.print("Current Position: ");
      Serial.print(positionLeft);
      Serial.println();

      inputState = 1;
    }
  }

  if (inputState == 3)
  {
    if(Serial.available())
    {
      Serial.println("Updating Carriage Position");
      desiredR = positionRight + Serial.parseInt();
      Serial.println("Position Updated");
      Serial.print("Desired Position: ");
      Serial.print(desiredR);
      Serial.println();
      Serial.print("Current Position: ");
      Serial.print(positionRight);
      Serial.println();

      inputState = 1;
    }
  }

}

  /* - - - - - - - - - - - - - - - - - - - - - - -
  /* manualMode()
  /*
  /* A function to control the motors based on the
  /* desired location.
  /* - - - - - - - - - - - - - - - - - - - - - - -
  */
  void manualMotor()
  {
```

```
    if (desiredS > positionLeft)
    {
      Motor2.forward();
      Motor2.power(scissorSpeed);

      if ((desiredS - positionLeft) <= 20)
      {
        Motor2.power(scissorSpeed/2);
      }
    }
    else if (desiredS < positionLeft)
    {
      Motor2.backward();
      Motor2.power(scissorSpeed/2);

      if ((desiredS - positionLeft) <= 20)
      {
        Motor2.power(scissorSpeed/2);
      }
    }
    else
    {
      Motor2.power(0);
    }


    if (desiredR > positionRight)
    {
      Motor1.forward();
      Motor1.power(carriageSpeed);

      if ((desiredR - positionRight) <= 20)
      {
        Motor1.power(carriageSpeed/2);
      }
    }
    else if (desiredR < positionRight)
    {
      Motor1.backward();
      Motor1.power(carriageSpeed);

      if ((desiredR - positionRight) <= 20)
      {
        Motor1.power(carriageSpeed/2);
      }
    }
    else
    {
      Motor1.power(0);
    }
  }
```

Motor Drivers

```
/* * * * * * * * * * * * * * * * * * * * * *
/* motor.h
/* Author: Tim Jung w/ Kelly Rorden and Edlin Garcia
/* Date Created: 4/26/2015
/* Last Edited: 5/27/2015
/*
/* A motor driver library writen in conjunction with team StarT.E.K.
/* for the Automatic Diffraction Grating Project - A Senior Project at
/* Cal Poly.
/*
/* Special Thanks to Kelly Rorden and Edlin Garcia
/* * * * * * * * * * * * * * * * * * * * * *
*/
#ifndef motor_h
#define motor_h
class motor
{
  public:
    motor(int in1, int in2, int standby, int pwm_a);
    void forward();
    void backward();
    void on();
    void off();
    void brake();
    void power(int power);

  private:
    int pin1;
```

```
   int pin2;
   int stby;
   int pwm_pin;
   int motor_speed;
};
#endif

/* * * * * * * * * * * * * * * * * * * * *
/* motor.cpp
/* Author: Tim Jung w/ Kelly Rorden and Edlin Garcia
/* Date Created: 4/26/2015
/* Last Edited: 5/27/2015
/*
/* A motor driver library writen in conjunction with team StarT.E.K.
/* for the Automatic Diffraction Grating Project - A Senior Project at
/* Cal Poly.
/*
/* Special Thanks to Kelly Rorden and Edlin Garcia
/* * * * * * * * * * * * * * * * * * * * *
*/

#include "Arduino.h"
#include "motor.h"

motor::motor(int in1, int in2, int standby, int pwm_a)
{
  //Initilize pin variables
  pin1 = in1;
  pin2 = in2;
  stby = standby;
```

```
  pwm_pin = pwm_a;         //Set the PWM OUTPUT PIN #
  motor_speed = 0;         //Set initial SPEED to 0.

  //Initilize pins as outputs
  pinMode(pin1, OUTPUT);
  pinMode(pin2, OUTPUT);
  pinMode(stby, OUTPUT);
  pinMode(pwm_pin, OUTPUT);

  //Initilize the signals being sent by the arduino
  digitalWrite(pin1, LOW);
  digitalWrite(pin2, LOW);
  digitalWrite(stby, LOW);
  analogWrite(pwm_pin, 0);
}

/* - - - - - - - - - - - - - - - - - - - -
/* forward()
/*
/* A function to turn the motor forward (CW) Yippie!
/* - - - - - - - - - - - - - - - - - - - -
*/

void motor::forward()
{
  digitalWrite(pin1, HIGH);
  digitalWrite(pin2, LOW);
}

/* - - - - - - - - - - - - - - - - - - - -
```

```
/* backward()
/*
/* A function to turn the motor backward (CCW)
/* If you plug it in right...
/* - - - - - - - - - - - - - - - - - - - -
*/

void motor::backward()
{
  digitalWrite(pin1, LOW);
  digitalWrite(pin2, HIGH);
}

/* - - - - - - - - - - - - - - - - - - - -
/* on()
/*
/* Turns the motor on. Surprise!
/* - - - - - - - - - - - - - - - - - - - -
*/

void motor::on()
{
  digitalWrite(stby, HIGH);
}

/* - - - - - - - - - - - - - - - - - - - -
/* off()
/*
/* Turns the motor off. Like the lights. Like Batman.
/* - - - - - - - - - - - - - - - - - - - -
```

```
*/

void motor::off()
{
  digitalWrite(stby, LOW);
}

/* - - - - - - - - - - - - - - - - - - - -
/* power()
/*
/* Sets the pwm controling the motor (speed (or power))
/* - - - - - - - - - - - - - - - - - - - -
*/

void motor::power(int power)
{
  motor_speed = power;

  analogWrite(pwm_pin, motor_speed);
}
```

Encoder Drivers

```
/* Encoder Library, for measuring quadrature encoded signals
 * http://www.pjrc.com/teensy/td_libs_Encoder.html
 * Copyright (c) 2011,2013 PJRC.COM, LLC - Paul Stoffregen <paul@pjrc.com>
 *
 * Version 1.2 - fix -2 bug in C-only code
 * Version 1.1 - expand to support boards with up to 60 interrupts
```

```
 * Version 1.0 - initial release
 *
 * Permission is hereby granted, free of charge, to any person obtaining a copy
 * of this software and associated documentation files (the "Software"), to deal
 * in the Software without restriction, including without limitation the rights
 * to use, copy, modify, merge, publish, distribute, sublicense, and/or sell
 * copies of the Software, and to permit persons to whom the Software is
 * furnished to do so, subject to the following conditions:
 *
 * The above copyright notice and this permission notice shall be included in
 * all copies or substantial portions of the Software.
 *
 * THE SOFTWARE IS PROVIDED "AS IS", WITHOUT WARRANTY OF ANY KIND, EXPRESS OR
 * IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF MERCHANTABILITY,
 * FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGEMENT. IN NO EVENT SHALL THE
 * AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY CLAIM, DAMAGES OR OTHER
 * LIABILITY, WHETHER IN AN ACTION OF CONTRACT, TORT OR OTHERWISE, ARISING FROM,
 * OUT OF OR IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN
 * THE SOFTWARE.
 */


#ifndef Encoder_h_
#define Encoder_h_

#if defined(ARDUINO) && ARDUINO >= 100
#include "Arduino.h"
#elif defined(WIRING)
#include "Wiring.h"
#else
```

```
#include "WProgram.h"
#include "pins_arduino.h"
#endif

#include "utility/direct_pin_read.h"

#if defined(ENCODER_USE_INTERRUPTS) || !defined(ENCODER_DO_NOT_USE_INTERRUPTS)
#define ENCODER_USE_INTERRUPTS
#define ENCODER_ARGLIST_SIZE CORE_NUM_INTERRUPT
#include "utility/interrupt_pins.h"
#ifdef ENCODER_OPTIMIZE_INTERRUPTS
#include "utility/interrupt_config.h"
#endif
#else
#define ENCODER_ARGLIST_SIZE 0
#endif



// All the data needed by interrupts is consolidated into this ugly struct
// to facilitate assembly language optimizing of the speed critical update.
// The assembly code uses auto-incrementing addressing modes, so the struct
// must remain in exactly this order.
typedef struct {
	volatile IO_REG_TYPE * pin1_register;
	volatile IO_REG_TYPE * pin2_register;
	IO_REG_TYPE          pin1_bitmask;
	IO_REG_TYPE          pin2_bitmask;
	uint8_t              state;
	int32_t              position;
```

```
} Encoder_internal_state_t;

class Encoder
{
public:
	Encoder(uint8_t pin1, uint8_t pin2) {
		#ifdef INPUT_PULLUP
		pinMode(pin1, INPUT_PULLUP);
		pinMode(pin2, INPUT_PULLUP);
		#else
		pinMode(pin1, INPUT);
		digitalWrite(pin1, HIGH);
		pinMode(pin2, INPUT);
		digitalWrite(pin2, HIGH);
		#endif
		encoder.pin1_register = PIN_TO_BASEREG(pin1);
		encoder.pin1_bitmask = PIN_TO_BITMASK(pin1);
		encoder.pin2_register = PIN_TO_BASEREG(pin2);
		encoder.pin2_bitmask = PIN_TO_BITMASK(pin2);
		encoder.position = 0;
		// allow time for a passive R-C filter to charge
		// through the pullup resistors, before reading
		// the initial state
		delayMicroseconds(2000);
		uint8_t s = 0;
		if (DIRECT_PIN_READ(encoder.pin1_register, encoder.pin1_bitmask)) s |= 1;
		if (DIRECT_PIN_READ(encoder.pin2_register, encoder.pin2_bitmask)) s |= 2;
		encoder.state = s;
#ifdef ENCODER_USE_INTERRUPTS
		interrupts_in_use = attach_interrupt(pin1, &encoder);
```

```
		interrupts_in_use += attach_interrupt(pin2, &encoder);
#endif
		//update_finishup();  // to force linker to include the code (does not work)
	}



#ifdef ENCODER_USE_INTERRUPTS
	inline int32_t read() {
		if (interrupts_in_use < 2) {
			noInterrupts();
			update(&encoder);
		} else {
			noInterrupts();
		}
		int32_t ret = encoder.position;
		interrupts();
		return ret;
	}
	inline void write(int32_t p) {
		noInterrupts();
		encoder.position = p;
		interrupts();
	}
#else
	inline int32_t read() {
		update(&encoder);
		return encoder.position;
	}
	inline void write(int32_t p) {
		encoder.position = p;
```

```
	}
#endif
private:
	Encoder_internal_state_t encoder;
#ifdef ENCODER_USE_INTERRUPTS
	uint8_t interrupts_in_use;
#endif
public:
	static Encoder_internal_state_t * interruptArgs[ENCODER_ARGLIST_SIZE];

//                  _______       _______
//        Pin1 ______|       |_______|       |______ Pin1
// negative <---     _______       _______       __     --> positive
//        Pin2 __|       |_______|       |_______|   Pin2

		//	new	new	old	old
		//	pin2	pin1	pin2	pin1	Result
		//	----	----	----	----	------
		//	0	0	0	0	no movement
		//	0	0	0	1	+1
		//	0	0	1	0	-1
		//	0	0	1	1	+2  (assume pin1 edges only)
		//	0	1	0	0	-1
		//	0	1	0	1	no movement
		//	0	1	1	0	-2  (assume pin1 edges only)
		//	0	1	1	1	+1
		//	1	0	0	0	+1
		//	1	0	0	1	-2  (assume pin1 edges only)
		//	1	0	1	0	no movement
		//	1	0	1	1	-1
```

```
		//	1	1	0	0	+2  (assume pin1 edges only)
		//	1	1	0	1	-1
		//	1	1	1	0	+1
		//	1	1	1	1	no movement
/*
	// Simple, easy-to-read "documentation" version :-)
	//
	void update(void) {
		uint8_t s = state & 3;
		if (digitalRead(pin1)) s |= 4;
		if (digitalRead(pin2)) s |= 8;
		switch (s) {
			case 0: case 5: case 10: case 15:
				break;
			case 1: case 7: case 8: case 14:
				position++; break;
			case 2: case 4: case 11: case 13:
				position--; break;
			case 3: case 12:
				position += 2; break;
			default:
				position -= 2; break;
		}
		state = (s >> 2);
	}
*/

private:
	static void update(Encoder_internal_state_t *arg) {
#if defined(__AVR__)
```

```
// The compiler believes this is just 1 line of code, so
// it will inline this function into each interrupt
// handler.  That's a tiny bit faster, but grows the code.
// Especially when used with ENCODER_OPTIMIZE_INTERRUPTS,
// the inline nature allows the ISR prologue and epilogue
// to only save/restore necessary registers, for very nice
// speed increase.
asm volatile (
        "ld     r30, X+"        "\n\t"
        "ld     r31, X+"        "\n\t"
        "ld     r24, Z"                 "\n\t"   // r24 = pin1 input
        "ld     r30, X+"        "\n\t"
        "ld     r31, X+"        "\n\t"
        "ld     r25, Z"                 "\n\t"  // r25 = pin2 input
        "ld     r30, X+"        "\n\t"  // r30 = pin1 mask
        "ld     r31, X+"        "\n\t"   // r31 = pin2 mask
        "ld     r22, X"                 "\n\t"   // r22 = state
        "andi   r22, 3"                 "\n\t"
        "and    r24, r30"               "\n\t"
        "breq   L%=1"                   "\n\t"   // if (pin1)
        "ori    r22, 4"                 "\n\t"   //       state |= 4
"L%=1:""and     r25, r31"               "\n\t"
        "breq   L%=2"                   "\n\t"   // if (pin2)
        "ori    r22, 8"                 "\n\t"   //       state |= 8
"L%=2:" "ldi    r30, lo8(pm(L%=table))""\n\t"
        "ldi    r31, hi8(pm(L%=table))""\n\t"
        "add    r30, r22"               "\n\t"
        "adc    r31, __zero_reg__"      "\n\t"
        "asr    r22"                    "\n\t"
        "asr    r22"                    "\n\t"
```

```
        "st     X+, r22"        "\n\t"  // store new state
        "ld     r22, X+"        "\n\t"
        "ld     r23, X+"        "\n\t"
        "ld     r24, X+"        "\n\t"
        "ld     r25, X+"        "\n\t"
        "ijmp"                          "\n\t"   // jumps to update_finishup()
        // TODO move this table to another static function,
        // so it doesn't get needlessly duplicated.  Easier
        // said than done, due to linker issues and inlining
"L%=table:"                             "\n\t"
        "rjmp   L%=end"                         "\n\t"   // 0
        "rjmp   L%=plus1"               "\n\t"   // 1
        "rjmp   L%=minus1"              "\n\t"   // 2
        "rjmp   L%=plus2"               "\n\t"   // 3
        "rjmp   L%=minus1"              "\n\t"   // 4
        "rjmp   L%=end"                         "\n\t"   // 5
        "rjmp   L%=minus2"              "\n\t"   // 6
        "rjmp   L%=plus1"               "\n\t"   // 7
        "rjmp   L%=plus1"               "\n\t"   // 8
        "rjmp   L%=minus2"              "\n\t"   // 9
        "rjmp   L%=end"                         "\n\t"   // 10
        "rjmp   L%=minus1"              "\n\t"   // 11
        "rjmp   L%=plus2"               "\n\t"   // 12
        "rjmp   L%=minus1"              "\n\t"   // 13
        "rjmp   L%=plus1"               "\n\t"   // 14
        "rjmp   L%=end"                         "\n\t"   // 15
"L%=minus2:"                            "\n\t"
        "subi   r22, 2"                 "\n\t"
        "sbci   r23, 0"                 "\n\t"
        "sbci   r24, 0"                 "\n\t"
```

```
        "sbci   r25, 0"                 "\n\t"
        "rjmp   L%=store"               "\n\t"
    "L%=minus1:"                        "\n\t"
        "subi   r22, 1"                 "\n\t"
        "sbci   r23, 0"                 "\n\t"
        "sbci   r24, 0"                 "\n\t"
        "sbci   r25, 0"                 "\n\t"
        "rjmp   L%=store"               "\n\t"
    "L%=plus2:"                         "\n\t"
        "subi   r22, 254"               "\n\t"
        "rjmp   L%=z"                   "\n\t"
    "L%=plus1:"                         "\n\t"
        "subi   r22, 255"               "\n\t"
    "L%=z:" "sbci   r23, 255"           "\n\t"
        "sbci   r24, 255"               "\n\t"
        "sbci   r25, 255"               "\n\t"
    "L%=store:"                         "\n\t"
        "st     -X, r25"        "\n\t"
        "st     -X, r24"        "\n\t"
        "st     -X, r23"        "\n\t"
        "st     -X, r22"        "\n\t"
    "L%=end:"                           "\n"
    : : "x" (arg) : "r22", "r23", "r24", "r25", "r30", "r31");
#else
    uint8_t p1val = DIRECT_PIN_READ(arg->pin1_register, arg->pin1_bitmask);
    uint8_t p2val = DIRECT_PIN_READ(arg->pin2_register, arg->pin2_bitmask);
    uint8_t state = arg->state & 3;
    if (p1val) state |= 4;
    if (p2val) state |= 8;
    arg->state = (state >> 2);
```

```
		switch (state) {
			case 1: case 7: case 8: case 14:
				arg->position++;
				return;
			case 2: case 4: case 11: case 13:
				arg->position--;
				return;
			case 3: case 12:
				arg->position += 2;
				return;
			case 6: case 9:
				arg->position -= 2;
				return;
		}
#endif
	}
/*
#if defined(__AVR__)
	// TODO: this must be a no inline function
	// even noinline does not seem to solve difficult
	// problems with this.  Oh well, it was only meant
	// to shrink code size - there's no performance
	// improvement in this, only code size reduction.
	__attribute__((noinline)) void update_finishup(void) {
		asm volatile (
			"ldi	r30, lo8(pm(Ltable))"	"\n\t"
			"ldi	r31, hi8(pm(Ltable))"	"\n\t"
		"Ltable:"				"\n\t"
			"rjmp	L%=end"			"\n\t"	// 0
			"rjmp	L%=plus1"		"\n\t"	// 1
```

```
        "rjmp   L%=minus1"          "\n\t"  // 2
        "rjmp   L%=plus2"           "\n\t"  // 3
        "rjmp   L%=minus1"          "\n\t"  // 4
        "rjmp   L%=end"                     "\n\t"  // 5
        "rjmp   L%=minus2"          "\n\t"  // 6
        "rjmp   L%=plus1"           "\n\t"  // 7
        "rjmp   L%=plus1"           "\n\t"  // 8
        "rjmp   L%=minus2"          "\n\t"  // 9
        "rjmp   L%=end"                     "\n\t"  // 10
        "rjmp   L%=minus1"          "\n\t"  // 11
        "rjmp   L%=plus2"           "\n\t"  // 12
        "rjmp   L%=minus1"          "\n\t"  // 13
        "rjmp   L%=plus1"           "\n\t"  // 14
        "rjmp   L%=end"                     "\n\t"  // 15
"L%=minus2:"                        "\n\t"
        "subi   r22, 2"             "\n\t"
        "sbci   r23, 0"             "\n\t"
        "sbci   r24, 0"             "\n\t"
        "sbci   r25, 0"             "\n\t"
        "rjmp   L%=store"           "\n\t"
"L%=minus1:"                        "\n\t"
        "subi   r22, 1"             "\n\t"
        "sbci   r23, 0"             "\n\t"
        "sbci   r24, 0"             "\n\t"
        "sbci   r25, 0"             "\n\t"
        "rjmp   L%=store"           "\n\t"
"L%=plus2:"                         "\n\t"
        "subi   r22, 254"           "\n\t"
        "rjmp   L%=z"               "\n\t"
"L%=plus1:"                         "\n\t"
```

```
				"subi	r22, 255"		"\n\t"
			"L%=z:" "sbci	r23, 255"		"\n\t"
				"sbci	r24, 255"		"\n\t"
				"sbci	r25, 255"		"\n\t"
			"L%=store:"				"\n\t"
				"st	-X, r25"	"\n\t"
				"st	-X, r24"	"\n\t"
				"st	-X, r23"	"\n\t"
				"st	-X, r22"	"\n\t"
			"L%=end:"				"\n"
			: : : "r22", "r23", "r24", "r25", "r30", "r31");
		}
#endif
*/


#ifdef ENCODER_USE_INTERRUPTS
	// this giant function is an unfortunate consequence of Arduino's
	// attachInterrupt function not supporting any way to pass a pointer
	// or other context to the attached function.
	static uint8_t attach_interrupt(uint8_t pin, Encoder_internal_state_t *state) {
		switch (pin) {
		#ifdef CORE_INT0_PIN
			case CORE_INT0_PIN:
				interruptArgs[0] = state;
				attachInterrupt(0, isr0, CHANGE);
				break;
		#endif
		#ifdef CORE_INT1_PIN
			case CORE_INT1_PIN:
```

```
                interruptArgs[1] = state;
                attachInterrupt(1, isr1, CHANGE);
                break;
#endif
#ifdef CORE_INT2_PIN
        case CORE_INT2_PIN:
                interruptArgs[2] = state;
                attachInterrupt(2, isr2, CHANGE);
                break;
#endif
#ifdef CORE_INT3_PIN
        case CORE_INT3_PIN:
                interruptArgs[3] = state;
                attachInterrupt(3, isr3, CHANGE);
                break;
#endif
#ifdef CORE_INT4_PIN
        case CORE_INT4_PIN:
                interruptArgs[4] = state;
                attachInterrupt(4, isr4, CHANGE);
                break;
#endif
#ifdef CORE_INT5_PIN
        case CORE_INT5_PIN:
                interruptArgs[5] = state;
                attachInterrupt(5, isr5, CHANGE);
                break;
#endif
#ifdef CORE_INT6_PIN
        case CORE_INT6_PIN:
```

```
            interruptArgs[6] = state;
            attachInterrupt(6, isr6, CHANGE);
            break;
#endif
#ifdef CORE_INT7_PIN
      case CORE_INT7_PIN:
            interruptArgs[7] = state;
            attachInterrupt(7, isr7, CHANGE);
            break;
#endif
#ifdef CORE_INT8_PIN
      case CORE_INT8_PIN:
            interruptArgs[8] = state;
            attachInterrupt(8, isr8, CHANGE);
            break;
#endif
#ifdef CORE_INT9_PIN
      case CORE_INT9_PIN:
            interruptArgs[9] = state;
            attachInterrupt(9, isr9, CHANGE);
            break;
#endif
#ifdef CORE_INT10_PIN
      case CORE_INT10_PIN:
            interruptArgs[10] = state;
            attachInterrupt(10, isr10, CHANGE);
            break;
#endif
#ifdef CORE_INT11_PIN
      case CORE_INT11_PIN:
```

```
				interruptArgs[11] = state;
				attachInterrupt(11, isr11, CHANGE);
				break;
		#endif
		#ifdef CORE_INT12_PIN
			case CORE_INT12_PIN:
				interruptArgs[12] = state;
				attachInterrupt(12, isr12, CHANGE);
				break;
		#endif
		#ifdef CORE_INT13_PIN
			case CORE_INT13_PIN:
				interruptArgs[13] = state;
				attachInterrupt(13, isr13, CHANGE);
				break;
		#endif
		#ifdef CORE_INT14_PIN
			case CORE_INT14_PIN:
				interruptArgs[14] = state;
				attachInterrupt(14, isr14, CHANGE);
				break;
		#endif
		#ifdef CORE_INT15_PIN
			case CORE_INT15_PIN:
				interruptArgs[15] = state;
				attachInterrupt(15, isr15, CHANGE);
				break;
		#endif
		#ifdef CORE_INT16_PIN
			case CORE_INT16_PIN:
```

```
                interruptArgs[16] = state;
                attachInterrupt(16, isr16, CHANGE);
                break;
#endif
#ifdef CORE_INT17_PIN
        case CORE_INT17_PIN:
                interruptArgs[17] = state;
                attachInterrupt(17, isr17, CHANGE);
                break;
#endif
#ifdef CORE_INT18_PIN
        case CORE_INT18_PIN:
                interruptArgs[18] = state;
                attachInterrupt(18, isr18, CHANGE);
                break;
#endif
#ifdef CORE_INT19_PIN
        case CORE_INT19_PIN:
                interruptArgs[19] = state;
                attachInterrupt(19, isr19, CHANGE);
                break;
#endif
#ifdef CORE_INT20_PIN
        case CORE_INT20_PIN:
                interruptArgs[20] = state;
                attachInterrupt(20, isr20, CHANGE);
                break;
#endif
#ifdef CORE_INT21_PIN
        case CORE_INT21_PIN:
```

```
				interruptArgs[21] = state;
				attachInterrupt(21, isr21, CHANGE);
				break;
		#endif
		#ifdef CORE_INT22_PIN
			case CORE_INT22_PIN:
				interruptArgs[22] = state;
				attachInterrupt(22, isr22, CHANGE);
				break;
		#endif
		#ifdef CORE_INT23_PIN
			case CORE_INT23_PIN:
				interruptArgs[23] = state;
				attachInterrupt(23, isr23, CHANGE);
				break;
		#endif
		#ifdef CORE_INT24_PIN
			case CORE_INT24_PIN:
				interruptArgs[24] = state;
				attachInterrupt(24, isr24, CHANGE);
				break;
		#endif
		#ifdef CORE_INT25_PIN
			case CORE_INT25_PIN:
				interruptArgs[25] = state;
				attachInterrupt(25, isr25, CHANGE);
				break;
		#endif
		#ifdef CORE_INT26_PIN
			case CORE_INT26_PIN:
```

```
                interruptArgs[26] = state;
                attachInterrupt(26, isr26, CHANGE);
                break;
    #endif
    #ifdef CORE_INT27_PIN
        case CORE_INT27_PIN:
                interruptArgs[27] = state;
                attachInterrupt(27, isr27, CHANGE);
                break;
    #endif
    #ifdef CORE_INT28_PIN
        case CORE_INT28_PIN:
                interruptArgs[28] = state;
                attachInterrupt(28, isr28, CHANGE);
                break;
    #endif
    #ifdef CORE_INT29_PIN
        case CORE_INT29_PIN:
                interruptArgs[29] = state;
                attachInterrupt(29, isr29, CHANGE);
                break;
    #endif

    #ifdef CORE_INT30_PIN
        case CORE_INT30_PIN:
                interruptArgs[30] = state;
                attachInterrupt(30, isr30, CHANGE);
                break;
    #endif
    #ifdef CORE_INT31_PIN
```

```
		case CORE_INT31_PIN:
			interruptArgs[31] = state;
			attachInterrupt(31, isr31, CHANGE);
			break;
	#endif
	#ifdef CORE_INT32_PIN
		case CORE_INT32_PIN:
			interruptArgs[32] = state;
			attachInterrupt(32, isr32, CHANGE);
			break;
	#endif
	#ifdef CORE_INT33_PIN
		case CORE_INT33_PIN:
			interruptArgs[33] = state;
			attachInterrupt(33, isr33, CHANGE);
			break;
	#endif
	#ifdef CORE_INT34_PIN
		case CORE_INT34_PIN:
			interruptArgs[34] = state;
			attachInterrupt(34, isr34, CHANGE);
			break;
	#endif
	#ifdef CORE_INT35_PIN
		case CORE_INT35_PIN:
			interruptArgs[35] = state;
			attachInterrupt(35, isr35, CHANGE);
			break;
	#endif
	#ifdef CORE_INT36_PIN
```

```
		case CORE_INT36_PIN:
			interruptArgs[36] = state;
			attachInterrupt(36, isr36, CHANGE);
			break;
	#endif
	#ifdef CORE_INT37_PIN
		case CORE_INT37_PIN:
			interruptArgs[37] = state;
			attachInterrupt(37, isr37, CHANGE);
			break;
	#endif
	#ifdef CORE_INT38_PIN
		case CORE_INT38_PIN:
			interruptArgs[38] = state;
			attachInterrupt(38, isr38, CHANGE);
			break;
	#endif
	#ifdef CORE_INT39_PIN
		case CORE_INT39_PIN:
			interruptArgs[39] = state;
			attachInterrupt(39, isr39, CHANGE);
			break;
	#endif
	#ifdef CORE_INT40_PIN
		case CORE_INT40_PIN:
			interruptArgs[40] = state;
			attachInterrupt(40, isr40, CHANGE);
			break;
	#endif
	#ifdef CORE_INT41_PIN
```

```
		case CORE_INT41_PIN:
			interruptArgs[41] = state;
			attachInterrupt(41, isr41, CHANGE);
			break;
	#endif
	#ifdef CORE_INT42_PIN
		case CORE_INT42_PIN:
			interruptArgs[42] = state;
			attachInterrupt(42, isr42, CHANGE);
			break;
	#endif
	#ifdef CORE_INT43_PIN
		case CORE_INT43_PIN:
			interruptArgs[43] = state;
			attachInterrupt(43, isr43, CHANGE);
			break;
	#endif
	#ifdef CORE_INT44_PIN
		case CORE_INT44_PIN:
			interruptArgs[44] = state;
			attachInterrupt(44, isr44, CHANGE);
			break;
	#endif
	#ifdef CORE_INT45_PIN
		case CORE_INT45_PIN:
			interruptArgs[45] = state;
			attachInterrupt(45, isr45, CHANGE);
			break;
	#endif
	#ifdef CORE_INT46_PIN
```

```
        case CORE_INT46_PIN:
            interruptArgs[46] = state;
            attachInterrupt(46, isr46, CHANGE);
            break;
    #endif
    #ifdef CORE_INT47_PIN
        case CORE_INT47_PIN:
            interruptArgs[47] = state;
            attachInterrupt(47, isr47, CHANGE);
            break;
    #endif
    #ifdef CORE_INT48_PIN
        case CORE_INT48_PIN:
            interruptArgs[48] = state;
            attachInterrupt(48, isr48, CHANGE);
            break;
    #endif
    #ifdef CORE_INT49_PIN
        case CORE_INT49_PIN:
            interruptArgs[49] = state;
            attachInterrupt(49, isr49, CHANGE);
            break;
    #endif
    #ifdef CORE_INT50_PIN
        case CORE_INT50_PIN:
            interruptArgs[50] = state;
            attachInterrupt(50, isr50, CHANGE);
            break;
    #endif
    #ifdef CORE_INT51_PIN
```

```
        case CORE_INT51_PIN:
            interruptArgs[51] = state;
            attachInterrupt(51, isr51, CHANGE);
            break;
    #endif
    #ifdef CORE_INT52_PIN
        case CORE_INT52_PIN:
            interruptArgs[52] = state;
            attachInterrupt(52, isr52, CHANGE);
            break;
    #endif
    #ifdef CORE_INT53_PIN
        case CORE_INT53_PIN:
            interruptArgs[53] = state;
            attachInterrupt(53, isr53, CHANGE);
            break;
    #endif
    #ifdef CORE_INT54_PIN
        case CORE_INT54_PIN:
            interruptArgs[54] = state;
            attachInterrupt(54, isr54, CHANGE);
            break;
    #endif
    #ifdef CORE_INT55_PIN
        case CORE_INT55_PIN:
            interruptArgs[55] = state;
            attachInterrupt(55, isr55, CHANGE);
            break;
    #endif
    #ifdef CORE_INT56_PIN
```

```
				case CORE_INT56_PIN:
					interruptArgs[56] = state;
					attachInterrupt(56, isr56, CHANGE);
					break;
			#endif
			#ifdef CORE_INT57_PIN
				case CORE_INT57_PIN:
					interruptArgs[57] = state;
					attachInterrupt(57, isr57, CHANGE);
					break;
			#endif
			#ifdef CORE_INT58_PIN
				case CORE_INT58_PIN:
					interruptArgs[58] = state;
					attachInterrupt(58, isr58, CHANGE);
					break;
			#endif
			#ifdef CORE_INT59_PIN
				case CORE_INT59_PIN:
					interruptArgs[59] = state;
					attachInterrupt(59, isr59, CHANGE);
					break;
			#endif
				default:
					return 0;
			}
			return 1;
		}
#endif // ENCODER_USE_INTERRUPTS
```

```
#if defined(ENCODER_USE_INTERRUPTS) && !defined(ENCODER_OPTIMIZE_INTERRUPTS)
	#ifdef CORE_INT0_PIN
	static void isr0(void) { update(interruptArgs[0]); }
	#endif
	#ifdef CORE_INT1_PIN
	static void isr1(void) { update(interruptArgs[1]); }
	#endif
	#ifdef CORE_INT2_PIN
	static void isr2(void) { update(interruptArgs[2]); }
	#endif
	#ifdef CORE_INT3_PIN
	static void isr3(void) { update(interruptArgs[3]); }
	#endif
	#ifdef CORE_INT4_PIN
	static void isr4(void) { update(interruptArgs[4]); }
	#endif
	#ifdef CORE_INT5_PIN
	static void isr5(void) { update(interruptArgs[5]); }
	#endif
	#ifdef CORE_INT6_PIN
	static void isr6(void) { update(interruptArgs[6]); }
	#endif
	#ifdef CORE_INT7_PIN
	static void isr7(void) { update(interruptArgs[7]); }
	#endif
	#ifdef CORE_INT8_PIN
	static void isr8(void) { update(interruptArgs[8]); }
	#endif
	#ifdef CORE_INT9_PIN
```

```
static void isr9(void) { update(interruptArgs[9]); }
#endif
#ifdef CORE_INT10_PIN
static void isr10(void) { update(interruptArgs[10]); }
#endif
#ifdef CORE_INT11_PIN
static void isr11(void) { update(interruptArgs[11]); }
#endif
#ifdef CORE_INT12_PIN
static void isr12(void) { update(interruptArgs[12]); }
#endif
#ifdef CORE_INT13_PIN
static void isr13(void) { update(interruptArgs[13]); }
#endif
#ifdef CORE_INT14_PIN
static void isr14(void) { update(interruptArgs[14]); }
#endif
#ifdef CORE_INT15_PIN
static void isr15(void) { update(interruptArgs[15]); }
#endif
#ifdef CORE_INT16_PIN
static void isr16(void) { update(interruptArgs[16]); }
#endif
#ifdef CORE_INT17_PIN
static void isr17(void) { update(interruptArgs[17]); }
#endif
#ifdef CORE_INT18_PIN
static void isr18(void) { update(interruptArgs[18]); }
#endif
#ifdef CORE_INT19_PIN
```

```
static void isr19(void) { update(interruptArgs[19]); }
#endif
#ifdef CORE_INT20_PIN
static void isr20(void) { update(interruptArgs[20]); }
#endif
#ifdef CORE_INT21_PIN
static void isr21(void) { update(interruptArgs[21]); }
#endif
#ifdef CORE_INT22_PIN
static void isr22(void) { update(interruptArgs[22]); }
#endif
#ifdef CORE_INT23_PIN
static void isr23(void) { update(interruptArgs[23]); }
#endif
#ifdef CORE_INT24_PIN
static void isr24(void) { update(interruptArgs[24]); }
#endif
#ifdef CORE_INT25_PIN
static void isr25(void) { update(interruptArgs[25]); }
#endif
#ifdef CORE_INT26_PIN
static void isr26(void) { update(interruptArgs[26]); }
#endif
#ifdef CORE_INT27_PIN
static void isr27(void) { update(interruptArgs[27]); }
#endif
#ifdef CORE_INT28_PIN
static void isr28(void) { update(interruptArgs[28]); }
#endif
#ifdef CORE_INT29_PIN
```

```
static void isr29(void) { update(interruptArgs[29]); }
#endif
#ifdef CORE_INT30_PIN
static void isr30(void) { update(interruptArgs[30]); }
#endif
#ifdef CORE_INT31_PIN
static void isr31(void) { update(interruptArgs[31]); }
#endif
#ifdef CORE_INT32_PIN
static void isr32(void) { update(interruptArgs[32]); }
#endif
#ifdef CORE_INT33_PIN
static void isr33(void) { update(interruptArgs[33]); }
#endif
#ifdef CORE_INT34_PIN
static void isr34(void) { update(interruptArgs[34]); }
#endif
#ifdef CORE_INT35_PIN
static void isr35(void) { update(interruptArgs[35]); }
#endif
#ifdef CORE_INT36_PIN
static void isr36(void) { update(interruptArgs[36]); }
#endif
#ifdef CORE_INT37_PIN
static void isr37(void) { update(interruptArgs[37]); }
#endif
#ifdef CORE_INT38_PIN
static void isr38(void) { update(interruptArgs[38]); }
#endif
#ifdef CORE_INT39_PIN
```

```
static void isr39(void) { update(interruptArgs[39]); }
#endif
#ifdef CORE_INT40_PIN
static void isr40(void) { update(interruptArgs[40]); }
#endif
#ifdef CORE_INT41_PIN
static void isr41(void) { update(interruptArgs[41]); }
#endif
#ifdef CORE_INT42_PIN
static void isr42(void) { update(interruptArgs[42]); }
#endif
#ifdef CORE_INT43_PIN
static void isr43(void) { update(interruptArgs[43]); }
#endif
#ifdef CORE_INT44_PIN
static void isr44(void) { update(interruptArgs[44]); }
#endif
#ifdef CORE_INT45_PIN
static void isr45(void) { update(interruptArgs[45]); }
#endif
#ifdef CORE_INT46_PIN
static void isr46(void) { update(interruptArgs[46]); }
#endif
#ifdef CORE_INT47_PIN
static void isr47(void) { update(interruptArgs[47]); }
#endif
#ifdef CORE_INT48_PIN
static void isr48(void) { update(interruptArgs[48]); }
#endif
#ifdef CORE_INT49_PIN
```

```
static void isr49(void) { update(interruptArgs[49]); }
#endif
#ifdef CORE_INT50_PIN
static void isr50(void) { update(interruptArgs[50]); }
#endif
#ifdef CORE_INT51_PIN
static void isr51(void) { update(interruptArgs[51]); }
#endif
#ifdef CORE_INT52_PIN
static void isr52(void) { update(interruptArgs[52]); }
#endif
#ifdef CORE_INT53_PIN
static void isr53(void) { update(interruptArgs[53]); }
#endif
#ifdef CORE_INT54_PIN
static void isr54(void) { update(interruptArgs[54]); }
#endif
#ifdef CORE_INT55_PIN
static void isr55(void) { update(interruptArgs[55]); }
#endif
#ifdef CORE_INT56_PIN
static void isr56(void) { update(interruptArgs[56]); }
#endif
#ifdef CORE_INT57_PIN
static void isr57(void) { update(interruptArgs[57]); }
#endif
#ifdef CORE_INT58_PIN
static void isr58(void) { update(interruptArgs[58]); }
#endif
#ifdef CORE_INT59_PIN
```

```
	static void isr59(void) { update(interruptArgs[59]); }
	#endif
#endif
};

#if defined(ENCODER_USE_INTERRUPTS) && defined(ENCODER_OPTIMIZE_INTERRUPTS)
#if defined(__AVR__)
#if defined(INT0_vect) && CORE_NUM_INTERRUPT > 0
ISR(INT0_vect) { Encoder::update(Encoder::interruptArgs[SCRAMBLE_INT_ORDER(0)]); }
#endif
#if defined(INT1_vect) && CORE_NUM_INTERRUPT > 1
ISR(INT1_vect) { Encoder::update(Encoder::interruptArgs[SCRAMBLE_INT_ORDER(1)]); }
#endif
#if defined(INT2_vect) && CORE_NUM_INTERRUPT > 2
ISR(INT2_vect) { Encoder::update(Encoder::interruptArgs[SCRAMBLE_INT_ORDER(2)]); }
#endif
#if defined(INT3_vect) && CORE_NUM_INTERRUPT > 3
ISR(INT3_vect) { Encoder::update(Encoder::interruptArgs[SCRAMBLE_INT_ORDER(3)]); }
#endif
#if defined(INT4_vect) && CORE_NUM_INTERRUPT > 4
ISR(INT4_vect) { Encoder::update(Encoder::interruptArgs[SCRAMBLE_INT_ORDER(4)]); }
#endif
#if defined(INT5_vect) && CORE_NUM_INTERRUPT > 5
ISR(INT5_vect) { Encoder::update(Encoder::interruptArgs[SCRAMBLE_INT_ORDER(5)]); }
#endif
#if defined(INT6_vect) && CORE_NUM_INTERRUPT > 6
ISR(INT6_vect) { Encoder::update(Encoder::interruptArgs[SCRAMBLE_INT_ORDER(6)]); }
#endif
#if defined(INT7_vect) && CORE_NUM_INTERRUPT > 7
ISR(INT7_vect) { Encoder::update(Encoder::interruptArgs[SCRAMBLE_INT_ORDER(7)]); }
```

```
#endif
#endif // AVR
#endif // ENCODER_OPTIMIZE_INTERRUPTS


#endif
```