Reliability of Torque and Temperature Feedback for an Autonomous Glass Monitoring System

by

Kaitlyn P. Becker

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the degree of

Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

June 2009

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Abstract

Automated pipe turners used in glassblowing studios are limited in their application by the duration a blown glass piece can be left unattended. An autonomous monitoring system can increase the usefulness of pipe turners in small studio and hobby settings, enabling glassblowers to work more independently. An initial feasibility study for an autonomous system has been performed by using two parameters, temperature measured by an IR thermometer and torque measured via the current drawn by a dc motor, to monitor glass blown objects during their production. The intended use of the system is for a glassblowing-pipe turning machine designed to keep a blown glass object centered about its axis of rotation and to keep the object heated within a set temperature range.

Temperature data was collected with a handheld IR thermometer for static and rotating samples with varying color additives and optic qualities. Some variation and noise was present in the temperature data, but the results were consistent enough to be readily implemented in an automated monitoring system. Torque feedback was monitored by recording the variation in current drawn by a dc motor that was mounted in a drive system to turn a glassblowing pipe. When a pipe carrying a misaligned piece was inserted in the drive system the data showed a recognizable oscillation corresponding to the varying torque due to gravitational forces on the rotating blown glass piece. This confirms that using the current drawn by the motor as alignment feedback will be feasible in an autonomous pipe turner.

This work can now be extended to modify the drive system that was used for testing to allow control of the axial position of the pipe and to integrate a digital micro controller which will be programmed to use the temperature and torque feedback to control the drive system.

Thesis Supervisor: Barbara Hughey, PhD
Title: Instructor in Mechanical Engineering

Acknowledgments

The author is grateful for all of the help and support she received while working on her thesis project.

She would like to thank the members of the MIT Glass Lab for their encouragement and feedback on the project, especially Martin Demaine, Peter Houk, and Mike Tarkanian. Also, Amy Nichols and Michael Stern, in particular, were enormously helpful throughout the project in assisting the author to setup and run tests in the Glass Lab.

The author is very thankful for the support and insight of Dr.Barbara Hughey, who enabled the author to pursue this project, which has been of personal interest to the author since her first year of exposure to hot glass in the MIT Glass Lab.

Introduction

Automated pipe turners are used in some glassblowing studios but are generally fixed speed devices without the capability to monitor the state of the glass piece being turned. The length of time that one of these existing pipe turners can be used to work a given piece is limited by the fact that the piece is not reheated. This leads to the glass cracking when left on the pipe turner for more than a couple minutes. In an attempt to prolong the length of this time window, the initial temperature of the glass can be increased before placing it on the turner. The risk of adding additional heat before placing a piece on the pipe turner is that the glass becomes softer, less stable, and more likely to become unbalanced in its rotations. The off-balance rotation makes it more difficult for a pipe turner to maintain even revolutions and often leads to deformation of the glass piece. So, while automated pipe turners can replace very basic tasks that would otherwise require an extra assistant, they would require a feedback system to monitor the temperature and alignment of the glass to be useful for a nontrivial length of time, at least five to ten minutes.

The fundamental design principle of the proposed monitoring system for an autonomous pipe turner is to increase the utility and functional time of such a device in order to facilitate more independent glassblowing. The present study is intended as a feasibility test for a simple and inexpensive system that could be integrated with existing equipment in the MIT Glass Lab in a way that minimizes the use of limited workspace. The goal of the autonomous pipe turner was originally to be an aid for short-handed production crews and to facilitate production work with smaller groups of people. The monitoring system uses an IR thermometer to measure the glass temperature, and the torque exerted by the glass on a rotating pipe as a measurement of alignment. As a relatively inexpensive alternative to a rotating torque sensor, the torque was measured through the drive system of the pipe turner by using the current pulled by a DC motor being run at a constant voltage.

Background

A Brief Overview of Glassblowing Terms and Pumpkin Production:

Glassblowing is a forming technique that involves the use of a blowpipe to inflate and shape molten glass. Glassblowing has developed into its modern form over a period of two millennia. The earliest development of blown glass dates back to the early first century A.D.. The American glassblowing movement, however, did not start until the early 1960s. Most glassblowing techniques practiced in studios in the United States are derived from Venetian glassblowing dating back to the 13th century [2]. Glassblowing includes a large set of equipment, tools, and terminology specific to the art, some of which still pays tribute to Venetian influences. A glossary of common terms that will be used throughout this document are included below.

Glass Terminology

Annealer, Annealing Oven

Oven used to slowly cool, sometimes heat, glass so as to minimize the internal stresses caused by uneven cooling rates and the thermal expansion/contraction of the glass.

Bar Color

Solid piece of colored glass that comes in rods approximately 1.5” to 2” thick.

Bench

Work bench where a glassblower does the majority of shaping of a piece. The bench has a set of rails on either side of the seat along which the blow pipe can be rolled while working.

Bit(s)

Additional pieces of glass brought hot and joined with a piece. Handles and pumpkin stems are examples of bits.

Blowpipe

Steel pipe used to carry, inflate, and manipulate a blown glass piece.

Center

On Center & Falling on Center

Aligning a piece with the axis of rotation of the pipe.

Off Center & Falling off Center

When a piece becomes misaligned.

Flash, flashing

A short heat in the glory hole meant to heat the entirety of a piece, including the moil.

Frit

Crushed colored glass. Molten clear class can be rolled in frit to apply color.

Figure 1. Glass frit.

Gaffer

Lead glassblower on a team. Usually, though not always, sits at the bench while others assist. Gaffer has primary responsibility for the pieces being made.

Gather

A gather or gathering is when a glassblower dips their blowpipe into the furnace. They turn the pipe while submerging the tip in the molten glass to add a layer of clear glass to their piece.

Glory Hole

Furnace resembling a large barrel turned on its side with a hole in the front face for heating/reheating blown glass pieces during the glassblowing process.

Figure 2. Glory Hole.

Moil

Portion of glass attaching a piece to the blowpipe. This is left on the pipe when the piece is later removed.

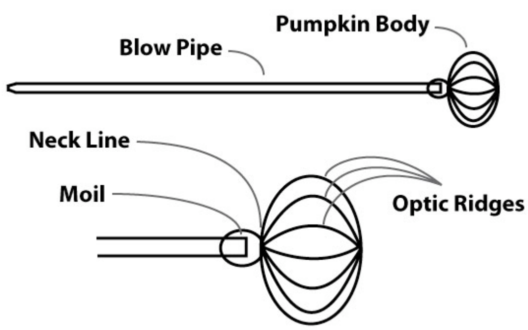

Figure 3. Pumpkin body on pipe on blowpipe.

Neckline

Ring where glass is squeezed down while rotating the pipe. This effectively creates a line around the glass similar to being synched together by a thin belt. The neckline near the pipe separates the moil and the piece, allowing them to later be broken apart when a piece is completed.

Starter

The person on production crew responsible for the first few steps of every piece.

Stemmer:

The person on a pumpkin production crew responsible for setting up stem to be attached by the gaffer.

Yoke

Stand in front of the glory hole with ball bearings to support the weight of the blowpipe while allowing rotation and axial translation while reheating piece.

Team Based Glassblowing and Assistance:

Work in the MIT Glass Lab is primarily done in teams of two to three people. This is typical of American glassblowing modeled after the team-oriented Venetian style. These teams include a primary person, called the gaffer, in charge of the piece being made and one or two assistants. Figure 4 shows two gaffers and their assistants, (a starter and stemmer,) on a production crew making pumpkins. The roles of the gaffer, stemmer and starter are explained in the next section.

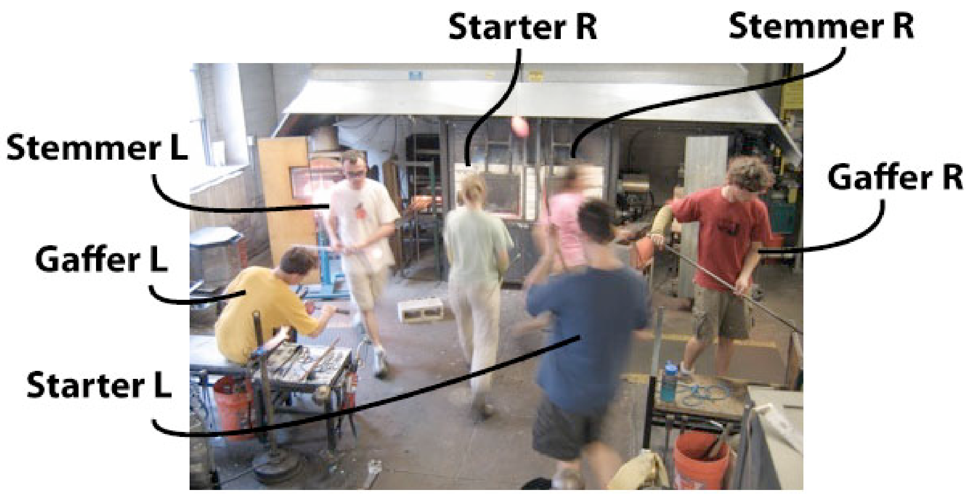

Figure 4. A pumpkin production crew of students and instructors in the MIT Glass Lab. Teams are labeled according to the bench they are working on, left and right.

Teamwork in the MIT glass lab is heavily emphasized in classes as well as on production crews where blown glass pumpkins are made for a fundraiser (figure 5). Production crews consist of six people split into two teams of three.

Figure 5. Left: Four students from the Glass Lab inflating pumpkin bodies on a production crew. Right: Approximately 1500 pumpkins being unpacked the evening before the MIT Great Glass Pumpkin Patch fundraiser.

Students and instructors in the glass lab work as volunteers on the pumpkin production crews throughout the year to prepare for the Great Glass Pumpkin Patch fundraiser for the lab each fall. When a crew working in the lab is short-handed, the efficiency of each person is reduced in addition to the productivity of the team altogether. A bench missing one out of three people will typically produce pumpkins at a rate less than two-thirds that of the full team of three. The loss in efficiency is primarily an issue of timing. With three people, large parts of the production can run in parallel. When a team is reduced to two people the steps can no longer be performed in parallel because the gaffer occasionally depends on an assistant. This forces the assistant to wait until one step is fully completed before starting another.

While the third person has a large effect on the productivity of the team, the division of work can be structured so that the tasks that third person is responsible for only require a basic skill level. Furthermore, it's possible for an experienced gaffer to take over all major components of the process in making a relatively simple pumpkin and use only one assistant for very basic tasks such as heating the body of the pumpkin and turning the pipe to keep the glass on center. Both of these tasks could be performed by an autonomous pipe turner in the interest of increasing the independence of the gaffer as well as saving the use of an assistant for other, more critical tasks.

<u>Overview of Pumpkin Production Crews in the MIT Glass Lab</u>

During the production crews for the Great Glass Pumpkin Patch in the MIT Glass Lab, the process of making a pumpkin is divided among three people. The division of tasks is shown in figure 6.

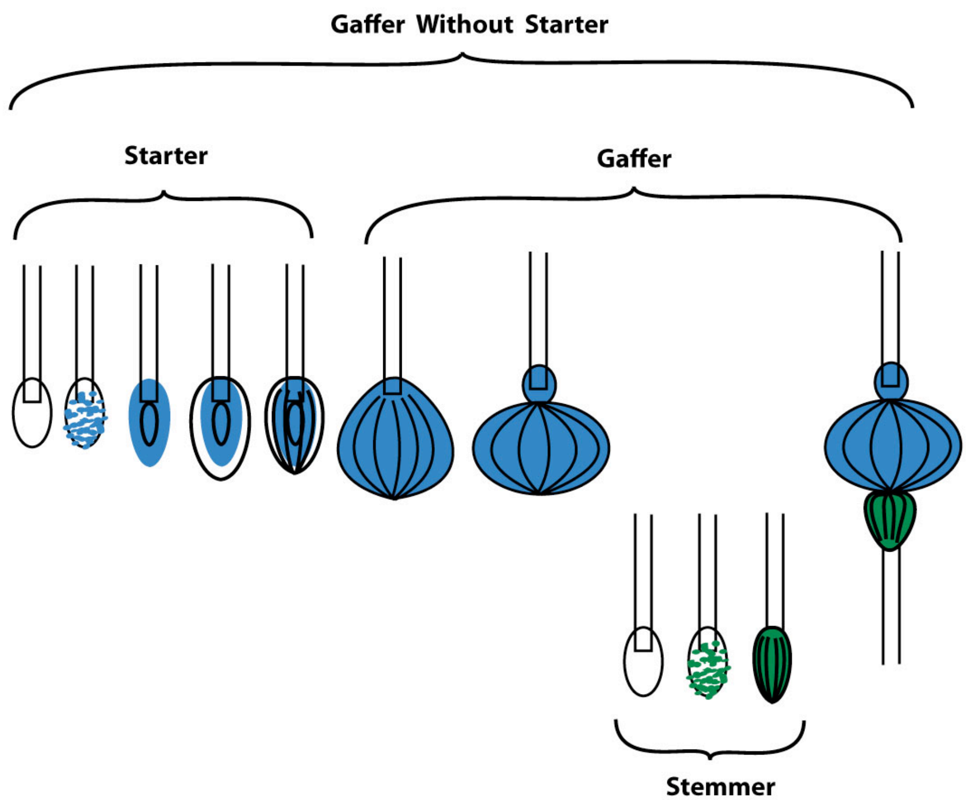

Figure 6. Stages of formation of a pumpkin and division of jobs for teams of two or three people.

A team usually consists of a gaffer, stemmer, and a starter. When a team of two people is making pumpkins, the gaffer will typically assume the starting responsibilities.

On a three-person team, the starter takes the first gather of clear glass, rolls it in frit to apply color, shapes the glass, blows a bubble and shapes the glass again. Depending on the size of the pumpkin they will take one or more additional gathers. After the final gather, the starter shapes the bubble again and blows it into a mold to create the optic ridges. During the process thus far, an experienced starter will typically reheat the piece between one and three times in the glory hole they share with the stemmer and gaffer. After they've added the color, started a bubble and created the optic ridges they pass the pumpkin start to the gaffer. As shown in figure 7, for the same three-person crew, the starter will take their first gather for the next pumpkin around the same time the stemmer starts gathering for a stem.

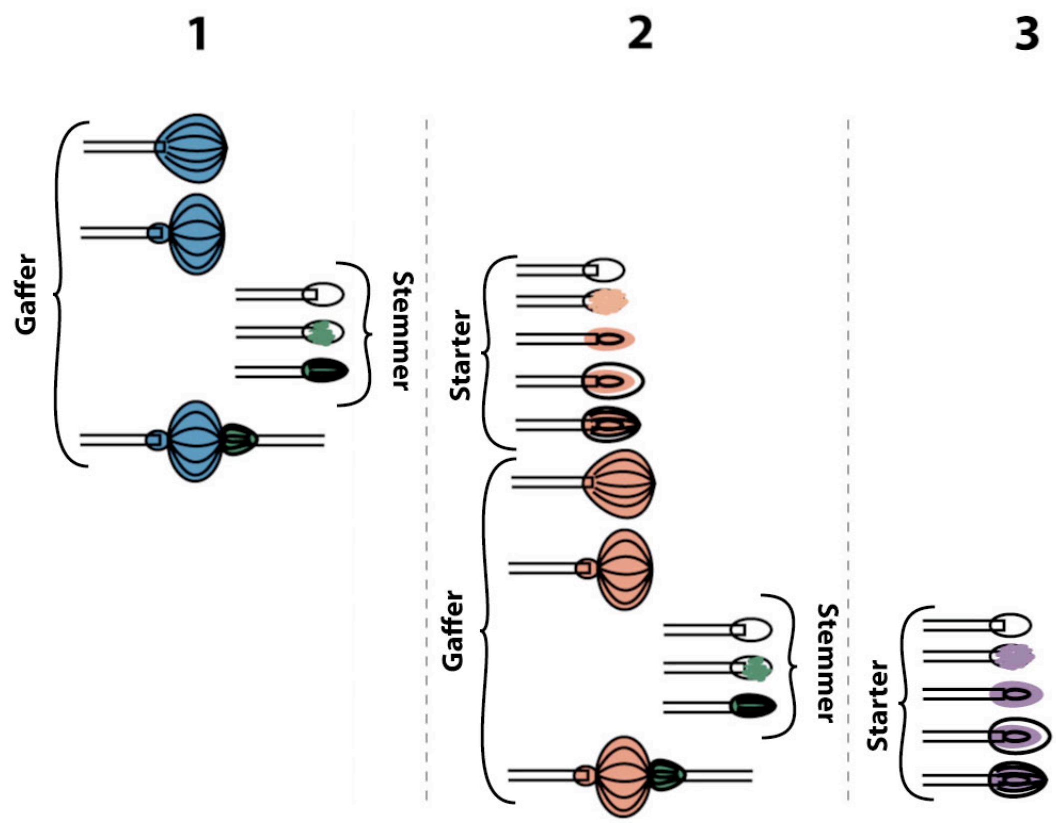

Figure 7. Diagram of timing for parallel production of blown glass pumpkins.

The gaffer inflates the ridged bubble they receive from the starter, shaping the pumpkin body and putting a neckline in where the pumpkin will later be broken off of the blowpipe. The air used to inflate the pumpkin can be provided by the stemmer or by the gaffer if they have an extension hose, which allows them to blow into the pipe while sitting at the bench. When ready, the gaffer asks for the stemmer to begin making the stem and flashes the pumpkin body until the stem is ready to be attached. A stem typically takes two gathers of glass, some color applied in the form of frit, and optic ridges from a small mold similar to the one used for the pumpkin body. A stem might require heating and shaping three times before going into the mold in order to build up the necessary heat distribution.

The time it takes to make a stem is the longest stretch during which the pumpkin could be placed in a pipe turner while the gaffer makes a stem instead of having an additional assistant. A very efficient stem with two gathers and some color takes at least three to four minutes to prepare. During this time the pumpkin needs to be reheated to prevent it from cracking and to keep it hot enough to attach the stem. If the glass is too cold but does not crack before the stem is applied, it is still at a high risk of cracking or prematurely breaking off of the blowpipe after the stem is finished.

The one point during the process of making a blown glass pumpkin where two glass blowers are needed simultaneously is for the attachment of the stem. Other wise, it is possible for instructors and students with experience working as starters for pumpkin crews to make a pumpkin without assistance in under twenty minutes. For one person to work completely through one pumpkin at a time does not create the highest volume output, but it is a more efficient use of each person individually because they are never waiting for another person to finish a given step. So, for a short-handed crew, one or two people could use a bench to make pumpkins more independently with the aid of a pipe turner for certain steps.

Monitoring Temperature and Alignment:

Glass blowers rely primarily on visual cues as indicators of the temperature and alignment of a piece. As shown in figure 8, a temperature difference can be judged by the color of the glass and moil, while alignment is seen as an eccentricity in the glass as the blowpipe is rotated, shown in figure 9.

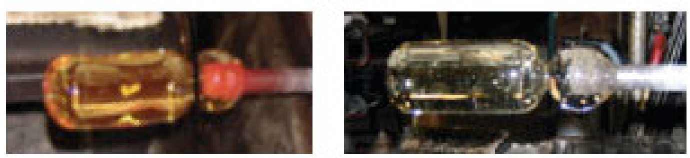

Figure 8. The left picture was taken while the piece was hot and moving. The right picture shows the piece when very cold relative to the left picture. Pictures are of a solid piece used for torque measurements.

Figure 9. Pumpkin body used for torque and temperature measurements. The black lines are inserted to emphasize stages of alignment of the piece.

These cues are conceptually simple to understand and implement but become complicated by the variability in the process. Irregular shapes, color application and glass types are factors that affect the appearance and thus the visual cues of the glass during the forming process. A glass blower with some experience can account for these factors but they pose a challenge to isolate in an autonomous glass monitoring system

To design a monitoring system capable of circumventing complexity due to variations between glass pieces, two parameters, non-contact IR temperature and torque measurements, were tested as indicators of temperature and alignment. The hypothesis behind the present study is that these two parameters are relatively independent of the color application and shape variations occurring between different blown glass pieces and could be implemented in a control system for an autonomous glassblowing pipe turner. Flexibility without human calibration requires the torque and temperature feedback to be unaffected by variations in the glass pieces. The original purpose of the autonomous pipe turner was for the production of blown glass pumpkins, but the intent of the present study is to test the use of non-contact IR and torque sensing for a system with flexibility to accommodate a variety of pieces of moderate size.

Maintaining the Temperature of a Glass Piece:

During the process of shaping a piece, the glass must be held within a certain temperature range. The glass used in the MIT Glass Lab is malleable and generally worked between 1200 F and 2100 F, depending on the piece being made and the preference of the gaffer. The piece is heated in a heat source called a glory hole, as shown in figure 10.

Figure 10. Pumpkin in front of glory hole with blowpipe resting on yoke.

If the glass is over-heated at any point the piece becomes unstable and can easily collapse. The glass is eventually cooled to room temperature but if it cools too quickly there is a buildup up internal stress caused by uneven thermal contraction [2]. The stress can crack the glass or, in some cases, cause it to explode. An example of this is shown in figure 11 below.

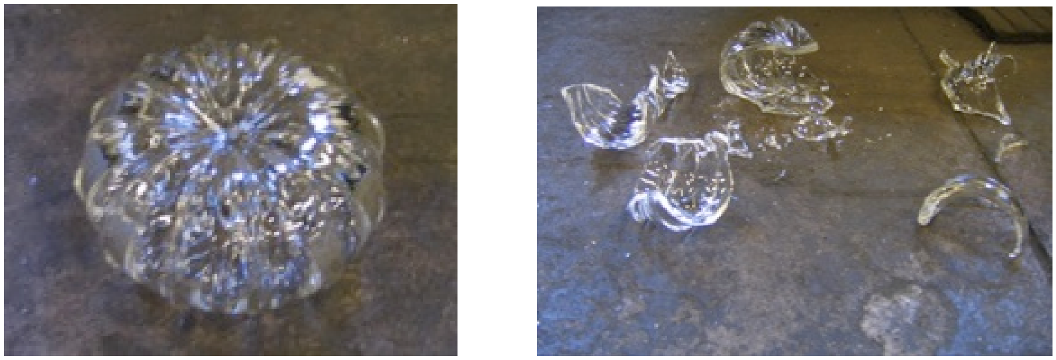

Figure11. Clear pumpkin body just after removed from pipe and placed on concrete floor (left). Same body untouched after several minutes (right).

When a glassblower is finished with a piece he or she is careful to allow the overall temperature of the piece fall while taking short heats, flashing their piece, to keep the surface, moil, and thin parts from cooling much faster than the insulated core or thicker parts. Once the piece is brought down near 900°F it is placed in annealing oven to finish slowly cooling the glass to room temperature[1]. This temperature is chosen based on the slumping temperature of the glass, at which the glass begins to visibly deform under the force of its weight [2].

While the temperature range at which the glass can be heated to maximize stability and avoid thermal shock can be fairly well defined, the varying thickness of blown glass objects and colorants in the glass may affect the ability to accurately monitor temperature and internal temperature gradients. The goal of this study is to measure the reliability with which an infrared sensor intended for surface temperature reading can be used to maintain glass blown objects with varying geometry and colorants within their acceptable range of temperature.

Temperature becomes more difficult to estimate when dealing with molten glass containing color. The colors affect the visible radiation of a heated piece and that effect varies between different colors. For example, blue and green colored glass will turn orange as they become hotter and radiate more heat, while other colors such as reds might turn darker or clear as they are heated. Different formulas of clear class without any color added may also appear different colors under the same heating conditions.

Non-contact IR Sensing

Non-contact IR sensors make use of an infrared (IR) detector to measure the electromagnetic radiation emitted by an object. More specifically, pyrometers typically use the area of the electromagnetic spectrum between approximately 0.78 μm, at the edge of the range of visible light, and 100 μm. In an idealized case, the object whose temperature is being measured can be approximated as a blackbody, which absorbs all incoming radiation and radiates according to the Stefan-Boltzmann-Law, where the total power emitted by a blackbody is proportional to the fourth power of the temperature of the body. Most objects, including glass, are actually grey bodies and emit less radiation than a black body for a given temperature. The emissivity of a grey body describes the level of radiation emitted in relation to that which would

[1] This temperature may vary slightly depending on the type of glass used, but 900F is used in the MIT glass lab and is a typical value used for studios.

be emitted by a black body. The non-contact sensor adjusts to different emissivity settings in order to calibrate the temperature measurement for a given material[1].

Approximate values of the emissivity of glass range between 0.92 and 0.97. One concern of the present study is whether added color may have a significant effect on the emissivity of the clear glass melted in the furnace of the MIT Glass Lab. Colored glass is produced by adding various metal oxides to the glass. There is typically a much greater volume of clear glass than colored glass for a given piece and the metal oxides compromise less than a percent of the total volume of the colored glass. At the same time, however, that small change in makeup of the glass is significant enough that a glass blower will alter the way (s)he heats and handles a given piece depending on the color application.

Maintaining Alignment of a Glass Piece:

One of the fundamental skills of a glassblower is to keep pieces aligned with the blowpipe, centered about the axis of rotation. In the studio this is referred to as 'keeping the piece on center.' To keep the piece on center, particularly when the glass is molten, the glassblower is nearly always rotating the pipe. A greater angular velocity becomes necessary as the piece is heated more and the glass becomes more fluidic, falling off center more quickly.

If the displacement of the center of mass of the glass from the axis of rotation becomes too large the piece may deform or become ruined. The magnitude at which a displacement becomes detrimental to a blown object is dependant on that object's geometry. The most common problems caused by a piece falling off center are warping of the overall shape and, for squat shapes, having the piece 'touch back' and reattach to the moil, creating an irregularly shaped connection point.

Factors Complicating Alignment:

There are several factors that complicate the task of keeping a piece on center. Noncircular bodies with radii that vary within a given cross section, for example, illustrated in figure 12, can make the centering of pieces an ambiguous task.

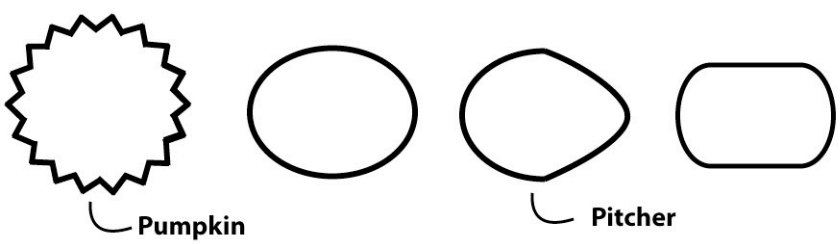

Figure 12. Noncircular piece cross-sections and variable radii.

Bits, such as handles or stems, are another factor that can make it more difficult to visually identify the center position of a piece. If large enough, they can also change the location of the center of mass so that it no longer intersects the center line of the body of a piece. Bits are usually added at the end of the process of making a piece for several reasons, one of which is to avoid warping the piece with the unbalanced forces associated with the weight of the bit.

Another, purely visual factor is any non-uniform or asymmetric color application, which adds a degree of confusion while watching a piece rotate. This is particularly true of spirals or straight lines that do not converge at a point on the axis of rotation. As a secondary effect, varied color distribution will also affect the shape of a piece because a soft color such as blue or black will stretch more than a stiff red or white when the piece is inflated.

Monitoring Alignment Via Torque:

The alignment of a blown glass piece can be monitored by the torque that it exerts on the pipe, which circumvents the difficulties of monitoring the alignment visually. If the glass blown object is not centered about its axis rotation it exerts a torque on the pipe that varies with its angular position, which is shown in figure 13.

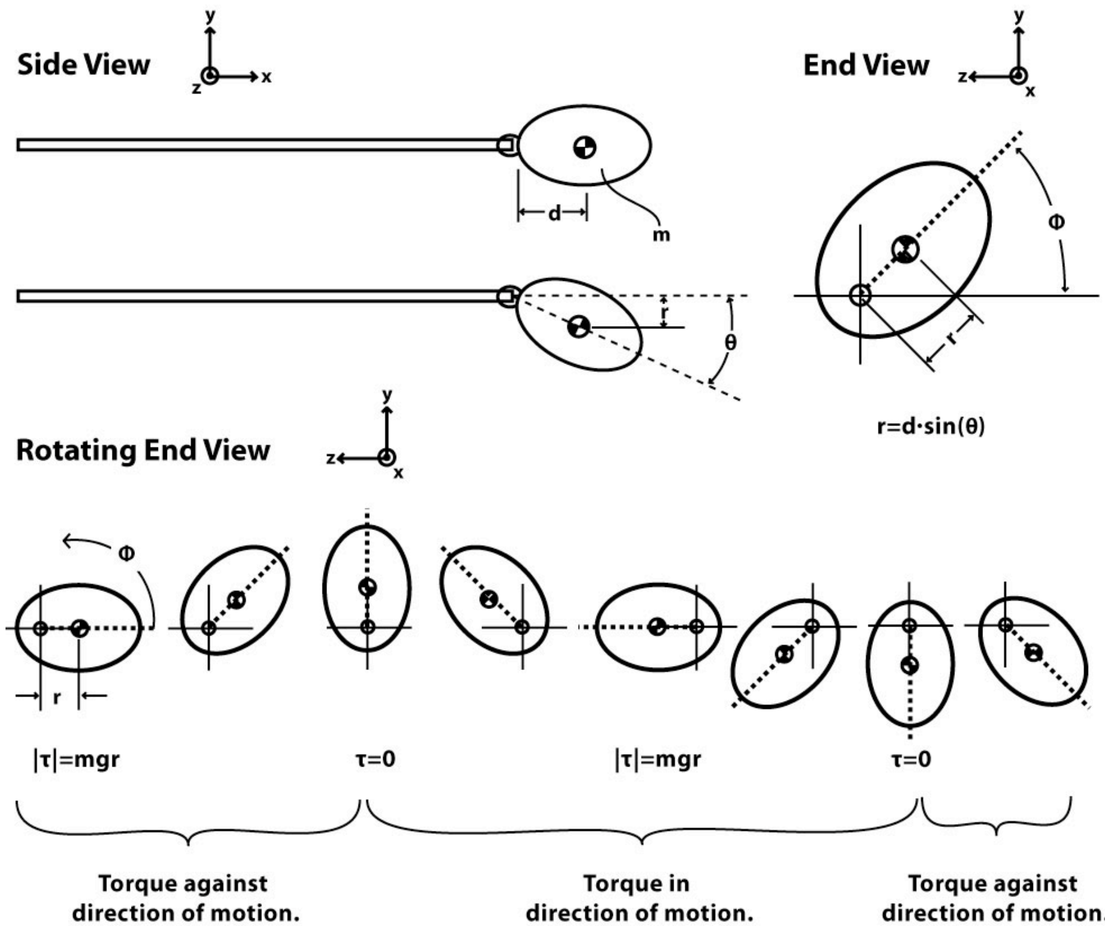

Figure 13. Off-center rotations of a glass piece.

The static torque exerted by an off center piece, as shown in figure 13, is given in equation 1, where m is the mass of glass, d is the distance from the axis of rotation to the center of mass, θ is the angular displacement of the center of mass from the axis of rotation, r is the equivalent linear displacement, and ϕ is the angular position:

$$r = d\sin(\theta) \tag{1}$$
$$\tau = mgr\cos(\theta) \tag{2}$$

A plot of the torque described by equation 2 is shown in figure 14 for an 8 cm tall piece weighing 2 kg with an angular displacement, θ, of 15 degrees.

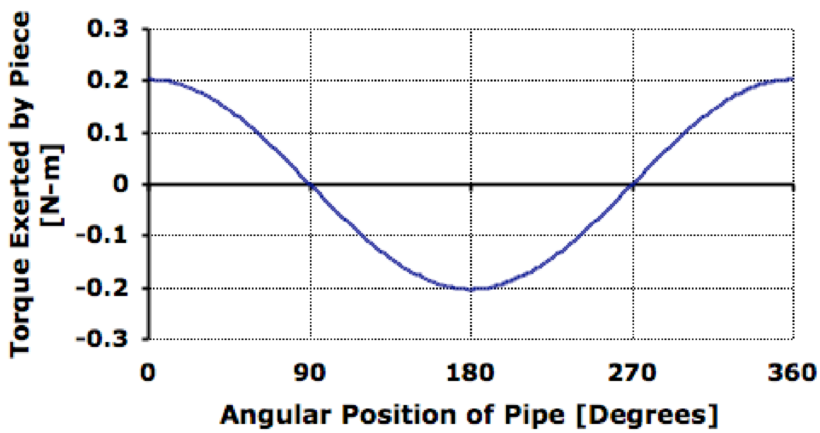

Figure 14. Idealized torque exerted by a 2 kg piece, 8 cm in height, skewed from the axis of rotation by 15 degrees.

While figure 14 depicts the torque exerted by the piece over a continuous period of time, the data collected by a torque sensor will show a discrete sample of points per time. Idealized illustrations of this are shown in figure 15 for a piece of the same dimensions as figure 14, rotating at approximately 34 rpm, with two different sample rates to show the need for sufficiently high rate of sampling in order to avoid aliasing.

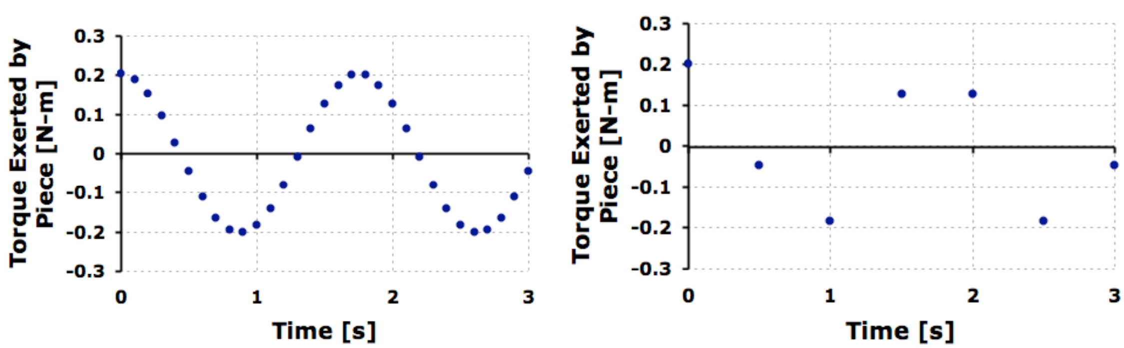

Figure 15. Idealized sampling feedback based on the torque in figure x-1 with a 1.75 second period for pipe revolution and a sampling rate of 10 Hz (on the left) and 2 Hz (on the right).

Replacing A Torque Sensor With A DC Motor:

A direct solution to measuring the torque of a rotating pipe is to use a rotating torque sensor. The decision not to use a rotating torque sensor for the present study was primarily motivated by cost. The price of a rotating torque sensor that would allow the appropriate motion was found to range up to several thousand dollars. This is an inappropriate expense in light of the budget for the present study as well as the intended use of the pipe turner as a piece of equipment to be used in a glass blowing studio. The goal is to design an assembly that could be built within a budget of a few hundred dollars given a set of plans and a suggested list of materials. The idea of a relatively low cost, 'do it yourself' set of plans is very common to glassblowing references, similar to ideas found in one of the most popular glass reference books, Glass Notes, by Henry Halem [3] as well as A Glassblower's Companion, A Compilation of Studio Equipment Designs, Essays, and Glassmaking Ideas by Dudley Giberson [2].

A DC motor was chosen as an inexpensive alternative to using a rotating torque sensor. A 12V dc motor with 10 in-lbs output with a built in gearbox reducing the speed to 50 rpm was purchased for under $50. Running at a constant speed and voltage, the current drawn by the motor can be measured as an indication of the output torque, which is directly related to the torque exerted by the piece. This relation is shown by equations 3, where T is the torque, K_T is the motor constant, and I is the current.

$$T = K_T I \tag{3}$$

According to equation 3, the torque exerted by the motor is proportional to the current drawn. This suggests that the current could be effectively substituted for torque as the parameter analyzed in a monitoring system for an autonomous glassblowing pipe turner.

The goal of the present study is to determine whether the variation in current drawn by a dc motor driving a pipe turner can be measured clearly enough with a current sensor to be effectively integrated into a glass monitoring system. Ideally, the signal measured by the current sensor should show a recognizable waveform that suggests a torque-position profile reminiscent of the idealized version shown in figure 14. With sufficient resolution of a waveform, it should be possible to predict the position of a misaligned glass piece starting from equations 1 and 2 and the angular velocity of the pipe.

Interpreting Feedback from a DC Motor:

An example of how a torque monitoring system via current measurement could be implemented is to send a 0-5V analog signal from the current sensor to a mini Arduino micro controller. Based on the illustration in figure 13 showing the off center rotations of a glass piece, the piece should transmit the maximum torque on the motor through the pipe and thus a maximum voltage reading when ϕ is π and the minimum torque when ϕ is zero. In order to correct the position of a misaligned piece, the motor should either pause at ϕ is equal to $\pi/2$ or it should move slower in the range 0 to π than the range π to 2π.

Experimental Setup

IR Testing:

IR Sensor

A hand held IR thermometer, (Extech model 42560), with a temperature range of -58°F to 1922°F was used to measure the glass temperature. The thermometer mode was set to record the max value readings with the assumption that the glass being measured should consistently be the hottest object within the line of sight. The emissivity calibration of the pyrometer was set to 0.95 for all of the measurements taken.

Static Temperature Tests

In order to examine the effect of IR temperature readings on glass color, a set of static readings were taken of eight varied colored samples at approximately 1000°F. The samples were heated in a top loading annealing oven in the MIT glass lab. The temperature indicated by thermocouples mounted in the annealing oven and the temperature measured by the pyrometer of both the brick insulation and the glass color samples were compared to evaluate the consistency of measurements. Figure 16 shows the set of color samples arranged on the floor of the annealing oven as well as an outside view of the annealing oven.

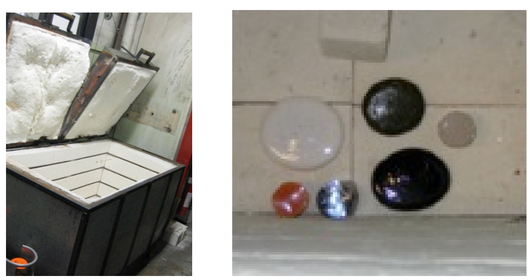

Figure 16. Top-loading annealing oven in MIT Glass Lab (left) and six of eight color samples in annealing oven (right).

The color samples shown in figure 16 include three solid pieces of color bar, three samples of frit coating a clear disc and two color sheets. Several of the colors were chosen with the anticipation that they might show significant differences based on experience of their behavior patterns when heated in blown glass pieces. The first two, Enamel White frit and White Bullseye sheet are comparatively stiff colors and require more heat to reach a malleable point. The Opalescent Black bar color and Black Bullseye sheet sit on the other end of the behavioral spectrum as very soft colors that heat up very quickly relative to the whites. Finally, the Lime Aventurine Green, which was used in one of the frit samples, has a very distinct behavior of its own. Aventurine colors contain larger metallic flecks to give the appearance of sparkles. The metal flecks increase the thermal conductivity of the glass, creating a faster transition between its frozen and molten state. When on the outer layer of glass, aventurines also leave a rougher surface finish.

Dynamic Temperature Tests with Color

Four samples were used to take tests comparing the effect of color on the temperature readings of a piece attached to a rotating pipe.

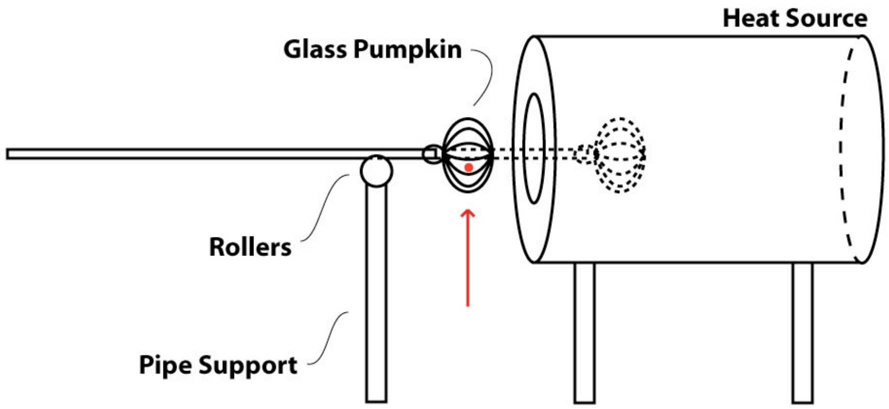

Figure 17. Schematic of heating and temperature sensing setup. The red arrow and dot indicate the target of the IR pyrometer.

A picture of three annealed samples is shown in figure 18 and an illustration of the testing setup is shown in figure 17 above.

Figure 18. Picture of annealed samples from dynamic temperature tests with color.

Multiple tests were taken for each sample with some variation on the amount of heat applied just before recording. Sample shapes were made with relatively straight walls at a constant radius from the center of rotation. The first sample was left clear as a control. Enamel White and Gaffer Black frit were applied to the second sample with an outer coating of clear glass. Enamel White and Lime Aventurine Green frit were applied to the outer surface of the third sample. The fourth sample, not shown, was half covered with gaffer black frit and half with clear.

Dynamic Temperature Tests with Optic Effects

Two samples were used to test the result of different optic effects on the temperature measurements. The first sample tested, shown later in figure 19, is a clear ellipsoid with optic ridges, a pumpkin body. The second sample was a cylinder with twisted optics ridges but was not annealed.

Cracking Temperature Tests

After removing the pumpkin body from the pipe in the previous set of tests, the moil was used for a 'cool to cracking' test. The moil was heated to even the temperature distribution because water was applied to the moil during the removal process to chill the neckline and facilitate a clean break. Once heated, the temperature of the moil was recorded until the point where it cracked, causing part of the remaining glass to pop off of the blowpipe.

***Torque testing**:*

Five samples pieces consisting of two pumpkin bodies and three solid cylinders were used to measure the variations of current drawn while rotating a pipe. The samples are shown below in figure 19.

Figure 19. Picture of samples used for torque testing. Ellipsoid with optics ridges, (pumpkin bodies), on top and solid cylinders on bottom.

Each of the samples were tested on center and off center to compare the measured torque profiles. Pictures of one pumpkin body at varying degrees of alignment are shown in figure 9 while pictures of the solid cylinders are shown in figure 20, below.

Figure 20. Pictures of pumpkin body and solid cylinders used for torque testing. Left hand images are on center and right hand images are off center.

For each of the torque tests, the pipes were driven at the end opposite the glass piece while the pipe was supported in the middle by the yoke, which is shown in figure 21.

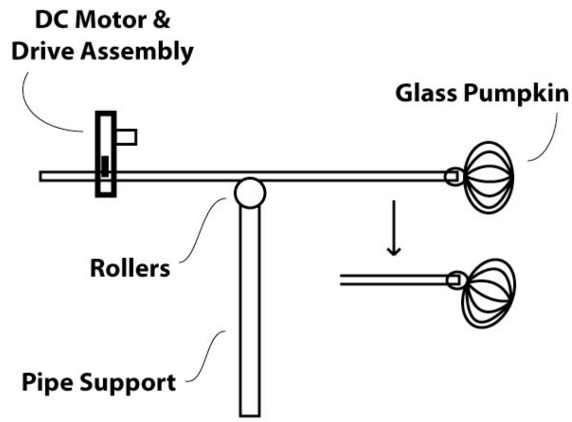

Figure 21. Schematic of drive and torque sensing setup

In this setup the yoke provides all of the normal force that supports the weight of the blowpipe and glass piece. The glass piece creates a torque on the pipe around the point of contact while the drive system provides the reactionary torque that keeps the pipe balanced. This orientation was chosen as way to integrate the drive system with the existing yoke and take advantage of the direction of the torque created by the gravitational force on the glass piece such that the pipe could be held in place against the drive system without needing to be more permanently secured. This is particularly important to allow the pipe to be put in or removed from the driven position with minimal effort in order to minimize the risk of damaging a piece.

The DC motor and drive assembly are shown below in figure 22. In the figure the assembly is turned upside down for a more clear view.

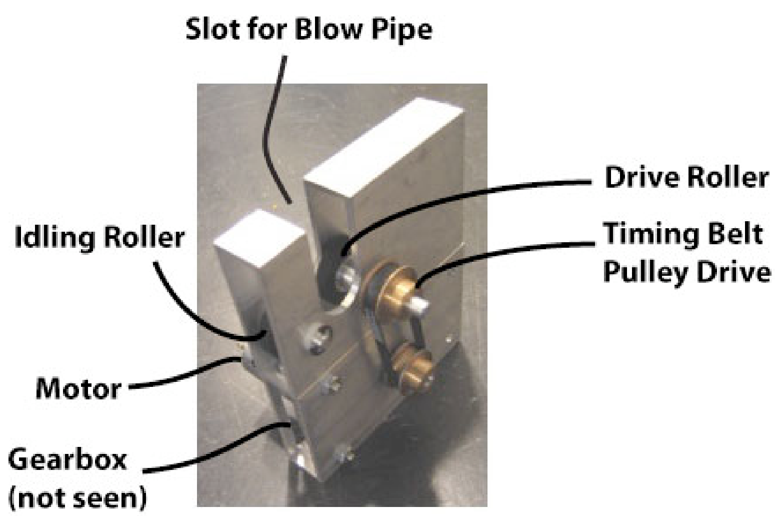

Figure 22. DC motor and drive assembly shown upside down for a better view of the components.

A compact DC gearmotor from Mcmaster Carr, rated for 12V, 50rpm, and 10in-lbs was used for the drive system. The turning motion was transmitted from the output shaft to the pipe via a timing belt assembly with 1.105" OD, 36 teeth pulleys and a 1/4" wide, 0.08" pitch timing belt. The pulley size was chosen to avoid interference with the rotating pipe that sits against neoprene drive and idling roller with an OD of 1.25". The assembly is housed in 5" lengths of 1"x3" aluminum box extrusion with 1/8" thickness. The connection between the two pieces is slotted on one side with a bolt hole on the other to allow for tensioning of the timing belt. Finally, a 1" slot was milled on the underside to position the pipe up against the neoprene rollers and prevent it from slipping out of position.

The motor current was recorded with a Vernier current sensor with 600 mA max current rating and a 0-5V output. The data were collected using Logger Pro and a 10 Hz sampling rate.

Results

IR Temperature Measurements:

Static color tests

Measurements from the static temperature tests are shown below in Figure 23. The static tests compared the thermocouple reading from the oven temperature monitoring system, IR reading of the color samples, and the IR readings of the brick insulation next to the samples.

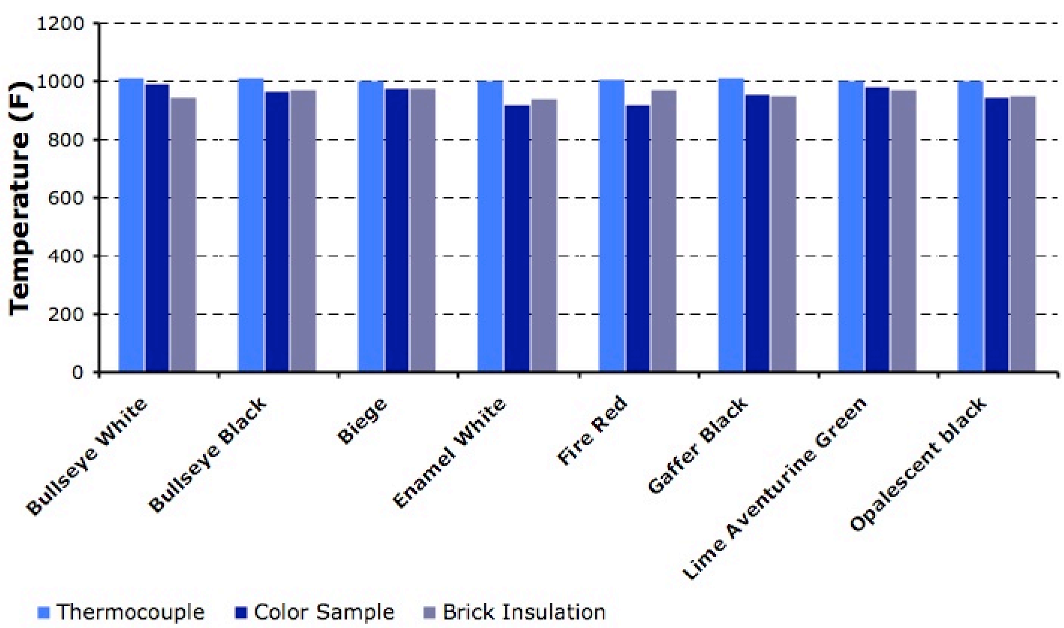

Figure 23. Static temperature test results comparing temperature measurements of thermocouples mounted in annealing oven, color samples, and brick insulation next to color samples.

The results show varying amounts of discrepancy under 10% for each of the color samples.

Dynamic color tests

A representative example of the dynamic color test from each of the four samples are shown in figures 24 through 27. The first, figure 24, is a clear (no color) test showing a short sample between flashing the piece in the glory hole as well as a series of temperature samples including the flashing periods when the piece is not in sight of the IR sensor.

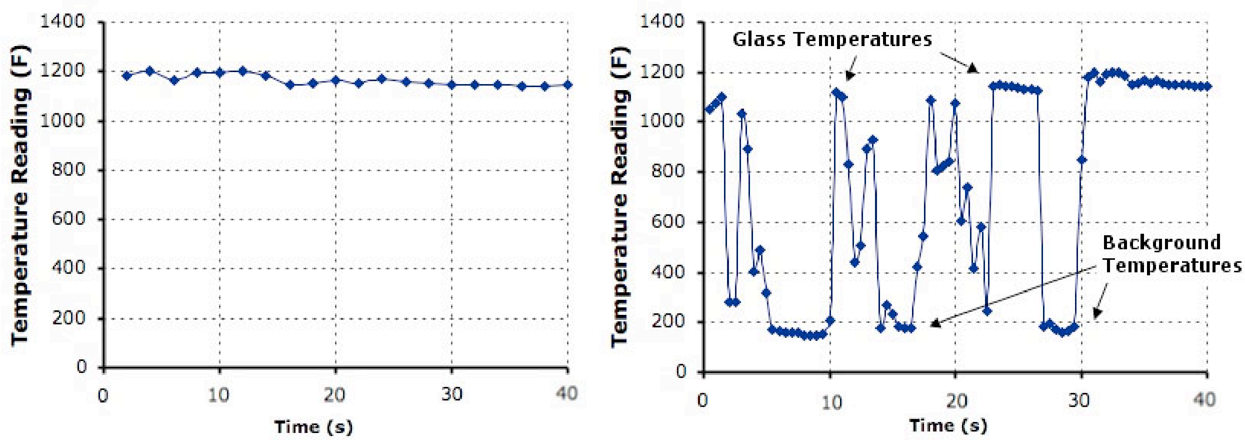

Figure 24. Clear cylinder dynamic (color) test. Graph on left shows one measurement set after flashing the piece. Graph on right shows measurements of pyrometer with piece moving in and out of view of the pyrometer, as it would look implemented in the pipe turner.

The first graph in figure 24 shows the actual temperature measurement of a piece while the second graph represents what an IR sensor fixed to the pipe turner would measure as the piece is moved in and out of the heat source (glory hole) over time in order to regulate the temperature of the piece. As the piece moves into the glory hole, it is out of sight of the IR sensor, so the temperature measured is that of the background. Some noise is present particularly in the latter of the clear sample graphs in figure 24 and is addressed in the discussion section.

The following two figures of the clear and Gaffer Black sample as well as the Gaffer Black and Enamel White sample show very little variation over the course of the test. The Enamel White and Lime Aventurine sample following, however, shows much more variation as the piece cools. Reasoning for this is given in the discussion of the present study.

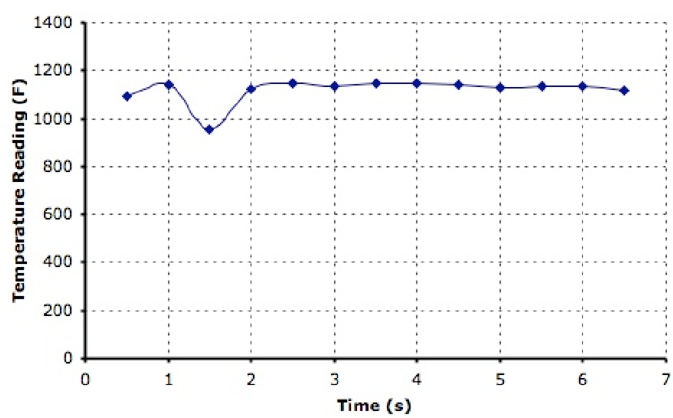

Figure 25. Gaffer black and clear dynamic color test.

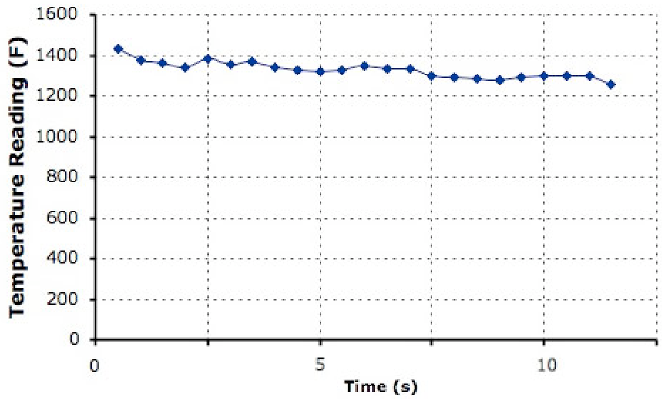

Figure 26. Gaffer black and enamel white dynamic color test.

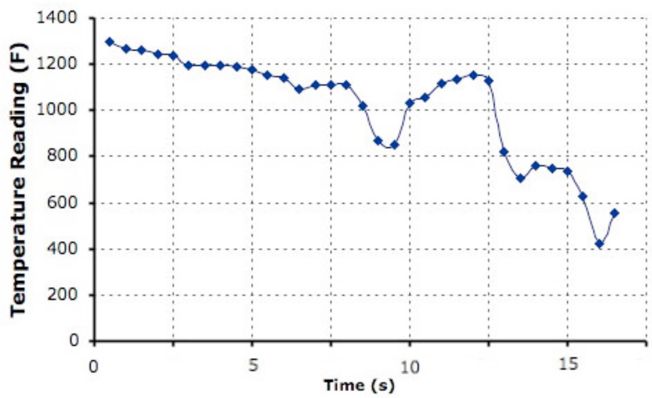

Figure 27. Enamel White and Lime Aventurine Green dynamic color test.

Dynamic testing with optic effects

A representative example of the temperature tests on a clear ellipsoid with optic ridges after flashing is in shown in figure 28. The graph on the right presents the same data on an expanded temperature scale. There is relatively little noise in the data.

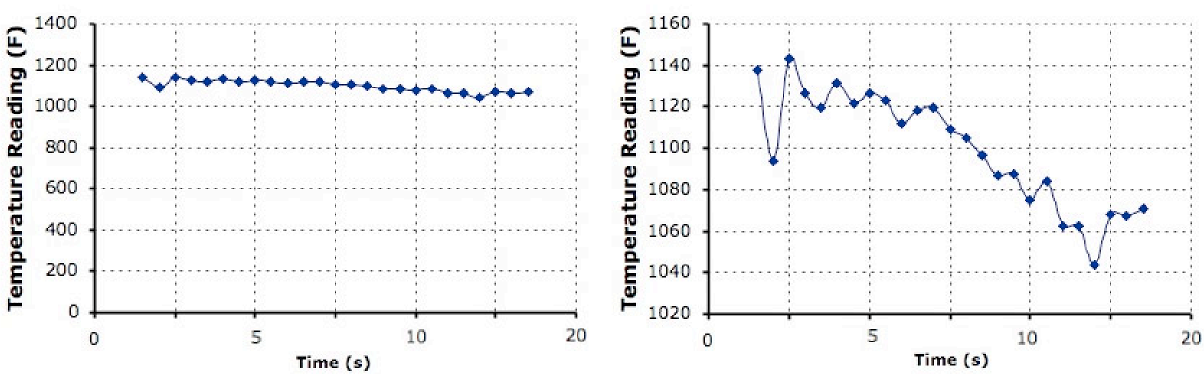

Figure 28. Temperature reading between heats of a clear ellipsoid with optic ridges, a clear pumpkin body. The data in the left and right hand graph are the same but presented in different temperature scales.

Cool to Cracking Test

The cool to cracking test is shown in figure 29 where the temperature of the moil of a pumpkin body was measured shortly after flashing to the point of cracking. Cracking occurred when then the temperature of the moil neared 600°F. The data recorded for this test appeared to be particularly noisy.

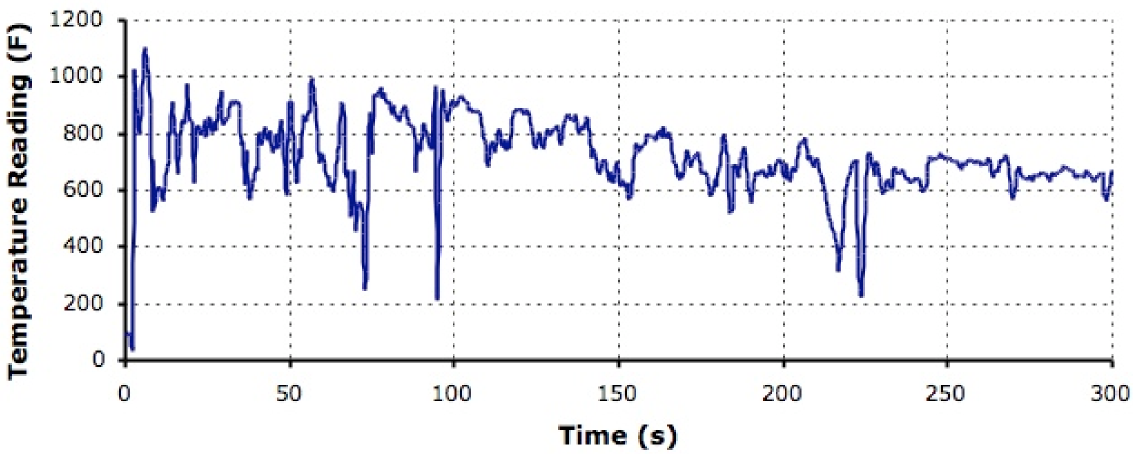

Figure 29. 'Cool to cracking' test. Temperature measurement of moil from pumpkin body until point where glass cracked and popped off of the pipe.

Torque Testing Measurements:

An example of the torque measurements taken with the smallest of the three solid cylinders in figure 19 while off center is shown below in figure 30. This data, taken at a 20 Hz sampling rate does not show a perfect sinusoid as depicted in the idealized version in figure, but does have a recognizable oscillation pattern in phase with the rotations of the pipe.

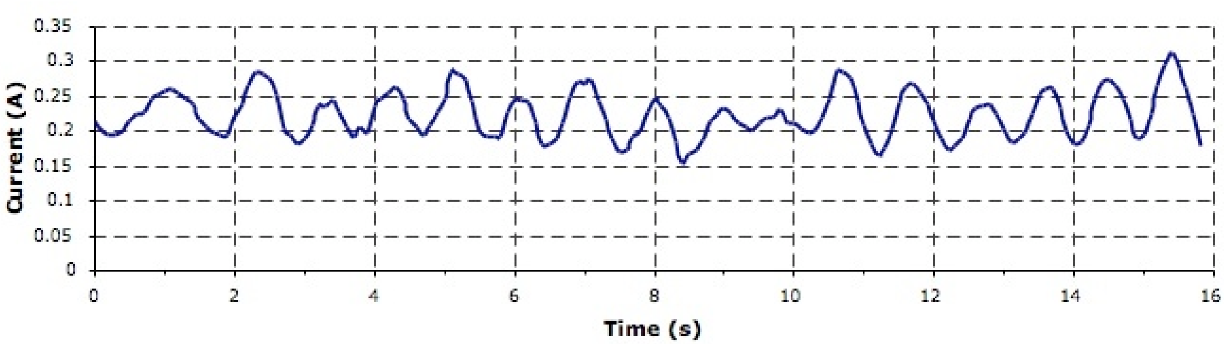

Figure 30. Record of current drawn while turning bottom right sample from figure x off center with dc motor at 12V.

A fast Fourier transform of the current measured from the off-center sample in figure 30 is shown below in figure 31.

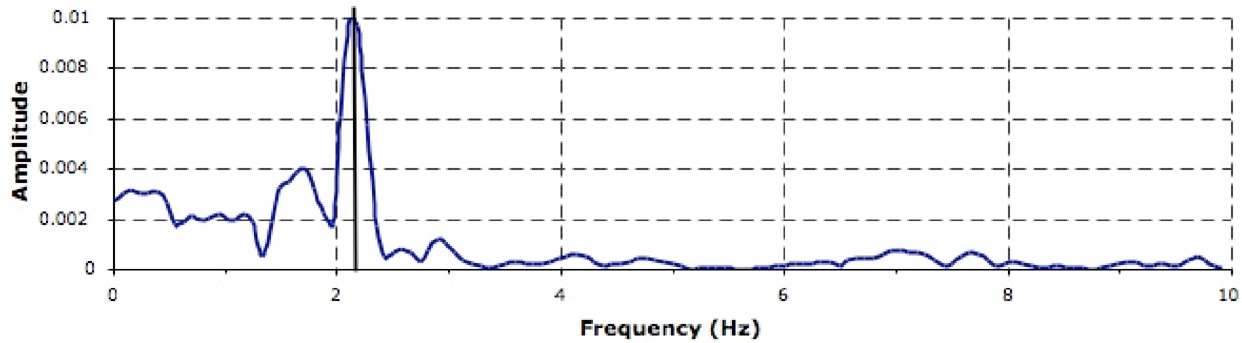

Figure 31. FFT of current measurements from off centered sample in figure 30.

The FFT shows that the dominant frequency of the current corresponds to the frequency of revolutions of the misaligned pieced turned by the motor, which was approximately two revolutions per second. By comparison, figures 32 and 33 show the current measurements from a centered piece and the related FFT.

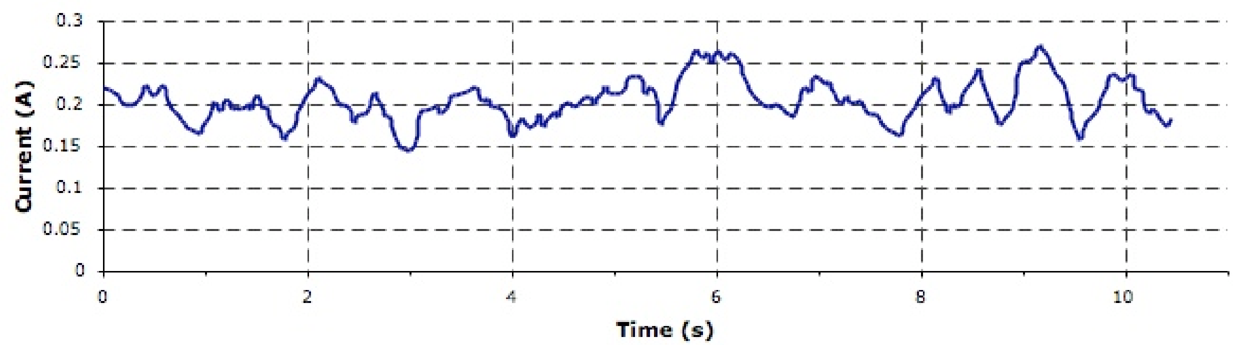

Figure 32. Record of current drawn while turning bottom right sample from figure x on center with dc motor at 12V.

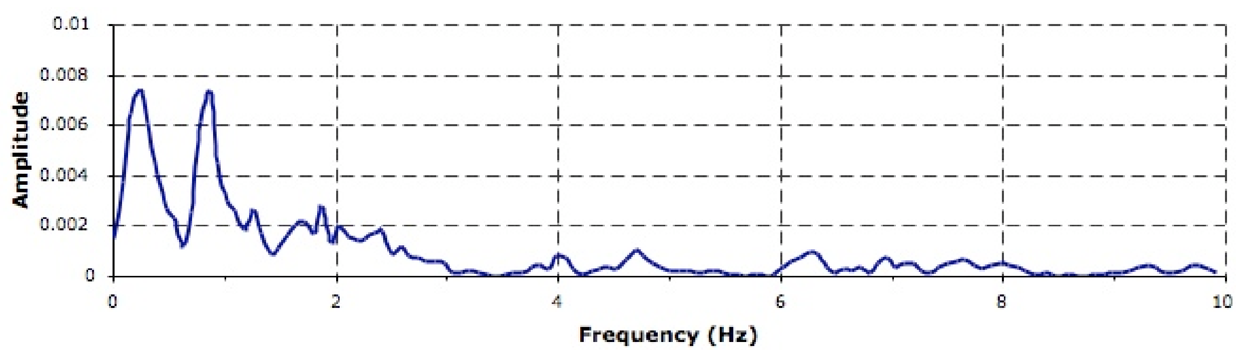

Figure 33. FFT of current measurements from centered sample in figure 32.

The current measured from a centered piece does not have a singular dominant frequency like the data from the off-center sample, nor is there an apparent increase in amplitude of frequencies near to that of the motor.

Discussion

Temperature Monitoring:

IR Temperature Sensing and Calibration

While there was some visible discrepancy among the values measured in the static temperature tests, the variations were small in comparison to the working temperature range of the glass. In glassblowing temperatures are typically estimated by eye by the glassblower without aid of sensors. As a result, the estimated temperature of a piece can vary by at least 100°F. In addition, the safe working range of a piece is several hundred degrees F.

The temperature of the oven as measured by the thermocouples fell between 5°F and 50°F each time the oven was opened to take measurements or for use of another project in progress at the same time as the static temperature tests. A possible result of this is that, while measurements were not taken until the thermocouple reading returned to approximately 1000°F, the heating elements may have more quickly heated the air surrounding the thermocouple and, having greater thermal mass, the color samples and the surrounding brick may have taken longer to return to the same target temperature.

Temperature variation in the dynamic color and optic effect tests also seemed to fall within a safe range for a monitoring system. Of the tests, the greatest variation was seen in the Enamel White and Lime Aventurine Green sample. Based on observations of the piece during testing and knowledge of the behavior of the two colors, it seems likely that the variation may be due to an actual variation in the color temperature as opposed to being purely correlated to the mechanics of IR temperature measurement. The composition of the Lime Aventurine green is such that it causes the glass piece to heat up and cool down more quickly. The fact that the colors for this test were also applied to the outside without an outer layer of clear also makes the effects of varying colors more pronounced than if they were encased on both sides by clear glass.

Based on the size of discrepancies and possible sources of error, the temperature variation seems neither unexpected nor unreasonable for the implementation of an IR sensor in a glass monitoring system for an autonomous pipe turner. The temperature variations seen in both the static and dynamic temperature tests seem to be small enough that they do not create a unsurpassable feasibility constraint on using an IR sensor for the temperature feedback on a blown glass object.

Noise and Troubleshooting Temperature Data Collection

The greatest source of noise while measuring the temperature of a piece was related to the use of the targeting feature of the IR thermometer. The red target that the IR device shines at the piece is intended to help with aiming the instrument and gauging the specific location of temperature being measured. The issue with relying on this lies in the fact that the light source and sensor location are offset from each other. While the two are positioned to intersect at a certain distance in front of the IR thermometer, the location of measurement may be slightly different than the location of the target. The area measured is also typically larger than the area represented by the target. Finally, in the clear and 'cool to cracking' test, additional noise was created by misalignment caused by difficulty determining whether the target light was passing through the glass or past the side of the glass and hitting objects in the background.

Optic ridges did not affect the temperature measurements of the IR thermometer, as should be expected by the fact that the sensor is not measuring the ability of light to permeate an object but, rather, the electromagnetic radiation coming off of the heated piece. The targeting feature, however, was adversely affected by optic ridges. The red target was split by the optic ridges and appeared in multiple locations, shifting around with the rotations of the piece. While this makes aiming more difficult, it does not otherwise affect IR measurements.

One option to reduce the noise due to error in aiming the IR thermometer caused by human error and ambiguity of the target position on the glass would be to choose a targeted area on the blowpipe, next to the moil. This would reduce ambiguity caused by optics effects of the glass. The temperature of the pipe can be correlated to the glass temperature and would give a conservative estimate of the glass temperature because it is coupled to the coldest part of a blown glass piece, (the moil). It should also show less variation with respect to angular position because the steel pipe has a higher thermal diffusivity than that of the glass, allowing the temperature to even out more quickly. In using the pipe as an alternative measuring point it should be noted that, while it should reduce the noise of measurements taken, it also creates the potential risk of biasing the measurements toward the cold side of the blown glass object. It is safer to accommodate for the coldest part of a blown glass piece when budgeting heating time to prevent cracking, but increases the likelihood of overheating the front side of the piece. The temperature monitoring system can be calibrated to ensure that a piece it heated properly for any chosen measurement location and some precautions can betaken to reduce the risk of developing adverse temperature gradients.

If the piece remains on the yoke whether in or out of the glory hole during the heating and cooling process it is always at risk of having the front overheat while the moil remains relatively cold, regardless of the location of temperature. This results from the higher heat flux incident on the front of the piece from the glory hole while the sides and back of the piece cool down more quickly. For this reason, glass blowers do not typically make use of the yoke in front of the glory hole unless specifically intending to heat the piece. Therefore it may be necessary to incorporate a heat shield in the design of the pipe automated turner to keep the front of the piece from continuing to heat between flashes while the moil is allowed to cool down. The longer the time period over which the pipe turner is used, the more important this shielding becomes.

Returning to the topic of noise reduction in the data, another solution that was implemented during data collection is to only use the maximum values recorded by the sensor. This relies on the fact that the molten glass piece being measured is most likely the hottest object within the line of sight of the IR sensor. This can correct for a small amount of inaccuracy while aiming the IR thermometer and would be relatively simple to implement in a control system.

Alignment Monitoring:

Most initial data recorded from the torque testing was noisy and unusable. More problematic than the noise in the initial tests, however, was the resolution of the current measurement versus angular velocity of the piece. During the tests, the pipe was turned by the drive system at a frequency of approximately 2 Hz. The initial sampling rate was limited to 1 Hz, which was insufficient to clearly decipher the positioning of the misaligned piece.

After switching to a different current sensor, the data shows a recognizable variation in the current measured, which can be related to the torque exerted by the pipe. In order to implement this type of measurement into a monitoring system it will be necessary to obtain a clearer signal from the current. In addition, the angular velocity produced by the motor should be decreased to better match typical speeds around 0.5 revolutions per second that a glassblower would use under normal conditions.

It may also be possible to filter the data collected by the current sensor to reduce noise in the results. The waveform seen in the current data is expected to show a sinusoidal pattern due to the varying torque as a result of the gravitational forces on a piece rotating off-center. The frequency of those oscillations should occur within a range of frequencies close to that of the angular velocity given by the specification of the motor while running under a load. It should be possible to use a band-pass filter in order to isolate that portion of the waveform for the purpose of identifying the orientation of the misaligned piece.

Conclusion

Feasibility

The results of the present study demonstrate that a control system for an autonomous pipe turner that relies on IR temperature sensing and the measurement of current drawn by a dc motor in the drive assembly can be developed with clearly understood modifications in the sensor system, especially for the torque feedback.

Project Continuation

Design and Construction

The next step is to complete the construction of the drive system so that it is fully integrated with the equipment existing in the MIT Glass Lab. The mounting system needs to be interfaced with the yoke, ideally with a mechanism that allows it to be adjusted to fit a range of dimensions. The mounting system will also need a mechanism to drive the pipe into and out of the heat source, which will likely be accomplished by adding a pivoting mechanism to the drive assembly. This mechanism will control the angle of wheels in the drive assembly with respect to the pipe. When the axis of rotation of the wheels is parallel to that of the pipe there is no axial motion. When the angle of the wheels is offset, the pipe is driven forward or backward depending on the direction of rotation of the pipe. This idea was taken from a related setup of roller bearings used in the MIT Glass Lab, which is depicted in figure 34 below.

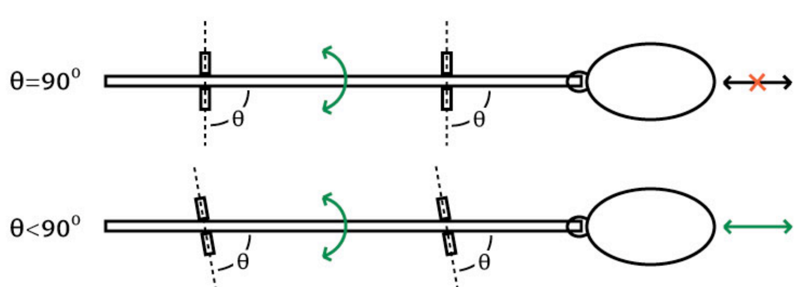

Figure 34. Depiction of angled roller setup to control axial motion of pipe.

The drive system will also be further refined from the testing setup into a more finished product in several ways. First, heat shielding will be added to prevent damage to the electrical and mechanical elements. The tolerances within the bearing system will also be refined to reduce the drift that was observed in the location of contact between the drive and idling rollers with the pipe. This drift occurred when the rollers became misaligned and began driving the pipe forward or backward. Finally, a clamping mechanism to increase the normal force between the dive wheels and the pipe will decrease the risk of slipping as well as increasing the allowable range of axial motion. The added normal force will increase the ability to couple the motor to the pipe for pieces that are otherwise too light to provide sufficient normal force the blowpipe and the drive system rollers.

Control and Programming

Once changes are made to the drive system to reduce the angular velocity of the pipe turner, an Arduino Mini microcontrollor board will be used to prototype a digital control system using a 0-5 Volt input from a non-contact IR temperature sensor and a current sensor. The primary objective of the next stage of development to amplify and filter the feedback from the current sensor such that the Arduino Mini can recognize a misalignment in the system. Once misalignment is recognizable and correctly interpreted, the logic to correct for it is relatively straightforward in that the pipe should either rotate more slowly when the signal moves from the highest to lowest value of current drawn or pause when the currents crosses the average current value directly after reaching the maximum value.

Summary

Once the monitoring demonstrated to be feasible in this study is successfully implemented with the modified drive system described above, the resulting automated pipe turner will be tested in the MIT Glass Lab and modified as needed until it fulfills its potential to expand the range of projects feasible for individual glassblowers and small teams. The final result will be an easy to install and use modular autonomous pipe turning system that can be built for hobby use for a few hundred dollars with minimal access to machining equipment.

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