Redesign of the Platform-Side Actuation System for the Kendall Band Interactive Musical Sculpture

by

Marian Heman-Ackah

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

February
2017

Signature of Author: ....Signature redacted....................
Department of Mechanical Engineering

Certified by: Signature redacted..
Barbara Hughey
Instructor, MIT Department of Mechanical Engineering
Thesis Supervisor

Certified by: .. Signature redacted ....
Mike Tarkanian
Senior Lecturer, MIT Department of Materials Science and Engineering
Thesis Supervisor

Certified by: .... Signature redacted.....................
Rohit Karnik
Associate Professor of Mechanical Engineering
Undergraduate Officer

Redesign of the Platform-Side Actuation System for the Kendall Band Interactive Musical Sculpture

by

Marian Heman-Ackah

Submitted to the Department of Mechanical Engineering
on February 27, 2017 in Partial Fulfillment of the
Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

ABSTRACT

The Kendall Band is an interactive musical sculpture by Paul Matisse located within the MBTA's Kendall/MIT Train Station. The sculpture, installed in 1987, consists of three instruments, Kepler, Galileo, and two sets of bells known as Pythagoras, each operated by its own system of mechanisms and linkages, and "played" by passengers using handles located on each platform. The sculpture as a whole has ceased to function as a result of a series of mechanical failures. Repair needs outpaced the resources available to maintain the sculpture. The primary known failure points are located within the portion of the actuation system on the platform of the station. Several components within this current actuation system are prone to fracture and wear. A new actuation system has been designed with various features that serve to increase overall durability, including a kinematic coupling with a spring-loaded interface that decouples actuation above a torque threshold of 225 in-lbf. Additionally, the newly designed actuation system has been standardized across all three instruments to simplify maintenance of the sculpture by incorporating a modular plate that has connection points for each instrument. Preliminary load testing performed upon a simplified version of the coupling interface proved promising for the design, but further work is required to prepare the design for installation.

Thesis Supervisors: Mike Tarkanian and Barbara Hughey

Tile: Redesign of the Platform-Side Actuation System for the Kendall Band Interactive Musical Sculpture

Acknowledgments

Many thanks to Paul Matisse, the original artist; Clarise Snyder for organizing funding for the project; my thesis supervisors Mike and Barbara; the Kendall Band Preservation Society, for their documentation of and work on the sculpture; the Edgerton Shop, for machining assistance; and my living group, Fourth East, for showering me with endless encouragement.

Table of Contents

List of Figures

Introduction

The Kendall Band, an interactive musical sculpture that resides within the Kendall/MIT MBTA Station, has entertained patrons of the Red Line since its installation in 1987. Unfortunately, time and wear have accelerated the repair needs of the sculpture. Despite a restoration effort in 2010, no group has taken on continued responsibility for the repairs needed to maintain the Kendall Band. A new design for the platform-side actuation is proposed to lessen the maintenance demands and increase the longevity of the three instruments that make up the sculpture. An improved design would incorporate the durability needed to withstand unexpected force introduced by passengers, as well as the fatigue from many loading cycles that occur each year when the instruments are played.

Background

1. Implementation and Preservation of the Kendall Band

The Kendall Band is an interactive musical sculpture created by artist Paul Matisse between 1986 and 1988. The sculpture, located between the train tracks of the Kendall/MIT subway station, was commissioned as a part of the "Arts on the Line" beautification program [1], an initiative to incorporate art pieces into the subway transit network of Boston. It consists of three instruments-- Pythagoras, Kepler, and Galileo (Fig. 1, next page). The three instruments are "played" by handles located on either side of the platform. A total of six handles are divided between the two platforms-- one for each half of Pythagoras, two for Kepler, and two for Galileo, allowing the instruments to be "played" from either side.

As Matisse [2] describes them:

> "Pythagoras is a series of 16 suspended aluminum tubes tuned to a B minor scale, with slight vibrato in each bell. Its handles can be used to slowly build the momentum of fourteen swinging teak mallets. When the mallets strike the tubes at random the tubes' musical notes reverberate throughout the station.
>
> Kepler is a heavy aluminum ring, 50" in diameter, whose 3-headed hammer makes it sound a low and resonant F#.
>
> Galileo is a large suspended sheet of metal: when shaken, it makes a sound of thunder."

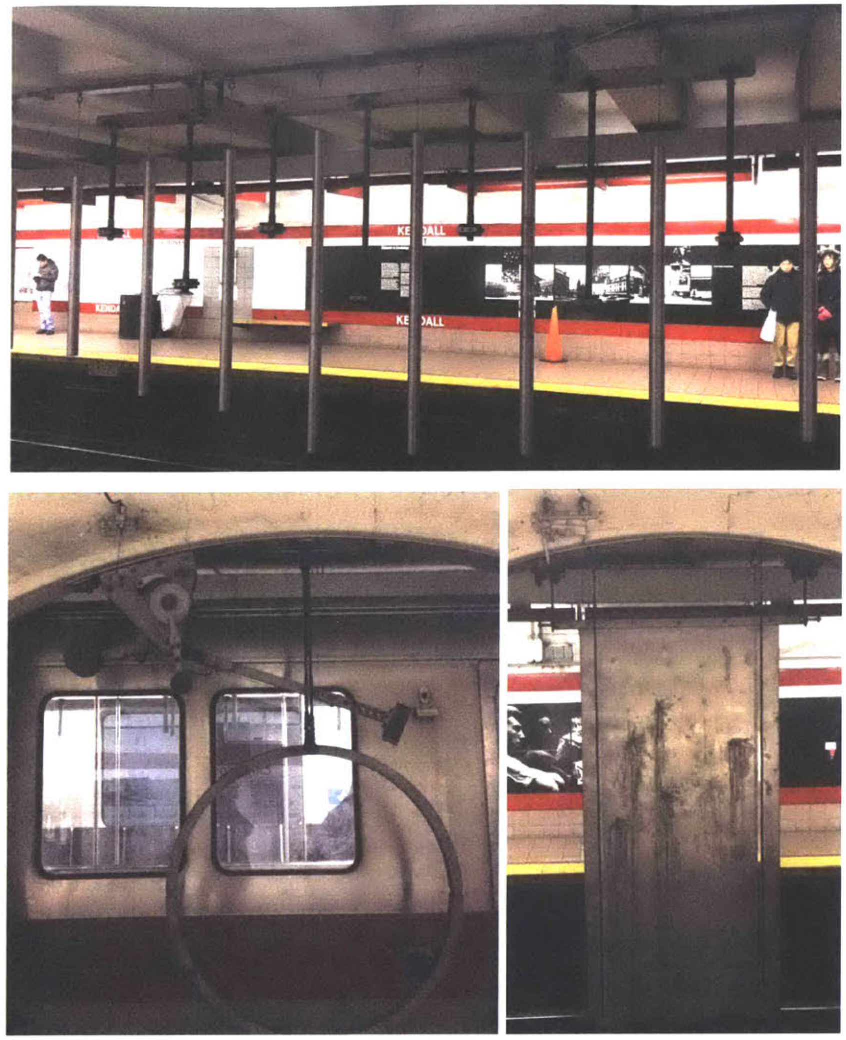

Figure 1: Half of Pythagoras (top), Kepler (bottom left), and Galileo (bottom right), within the Kendall station.

Soon after the the installation of the instruments began, significant maintenance issues arose. Matisse took it upon himself to repair the instruments and keep them in working order until 2007, at which point he was no longer able to maintain the sculpture [3].

1.1 Formation of and Restoration Efforts by the Kendall Band Preservation Society

The Kendall Band was abandoned until 2010, when Mike Tarkanian (MIT Department of Materials Science and Engineering) and Clarise Snyder (MIT Music and Theater Arts Section), responded to student interest in the sculpture's return, and helped organize an effort to document and repair the structure[4]. The group, known as the Kendall Band Preservation Society, returned Pythagoras to a fully functional state by 2011. With the help of Stephen Casentini, they created the Kendall Band Operation Manual, a guide designed to document the mechanical details of the sculpture and aid with repairs. The manual includes a full parts list for the sculpture, along with documentation of the installation and removal processes, maintenance records, and several technical drawings for each of the instruments. Despite the original efforts and intentions, student interest declined, and the group ceased to exist in 2013. Mike Tarkanian executed the repairs needed to keep Pythagoras running into 2014, at which point all maintenance efforts ceased.

2. Original Actuation System Design

2.1 Overview of the Sculpture Design and Original Instrument Actuation System

The overall architecture for all three instruments within the Kendall Band (Fig. 2) is highly similar. A handle on the platform is swung by a passenger, actuating a mechanism in a lower enclosure. This mechanism transfers motion to a second mechanism within the upper enclosure via a connecting rod. The upper mechanism connects to a third transfer mechanism that runs across the ceiling of the platform, which directly controls the object that "plays" the instrument.

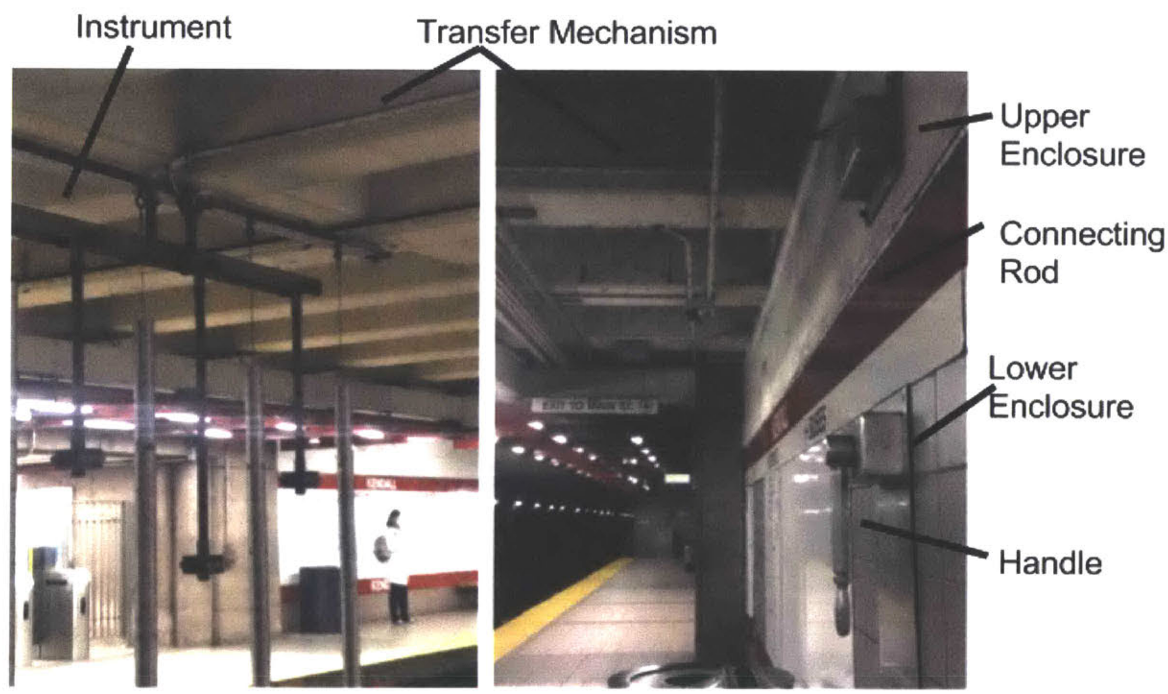

Figure 2: Kendall Band instrument architecture-- handle, platform enclosures, connecting rod (missing), transfer mechanism, and instrument.

The portion of the actuation system on the platform is fairly similar across the instruments as well. The enclosures for each instrument all feature a mechanism that rotates about a central pivot point, as shown in Figure 3. For all three instruments, the lower mechanism is a rocker with an attachment point for the connecting rod. The upper mechanism for Galileo is another rocker, modified with two hooks for its ceiling connector. For Pythagoras and Kepler, the upper mechanism incorporates a clutch-like device that disengages the actuation when subjected to a high load.

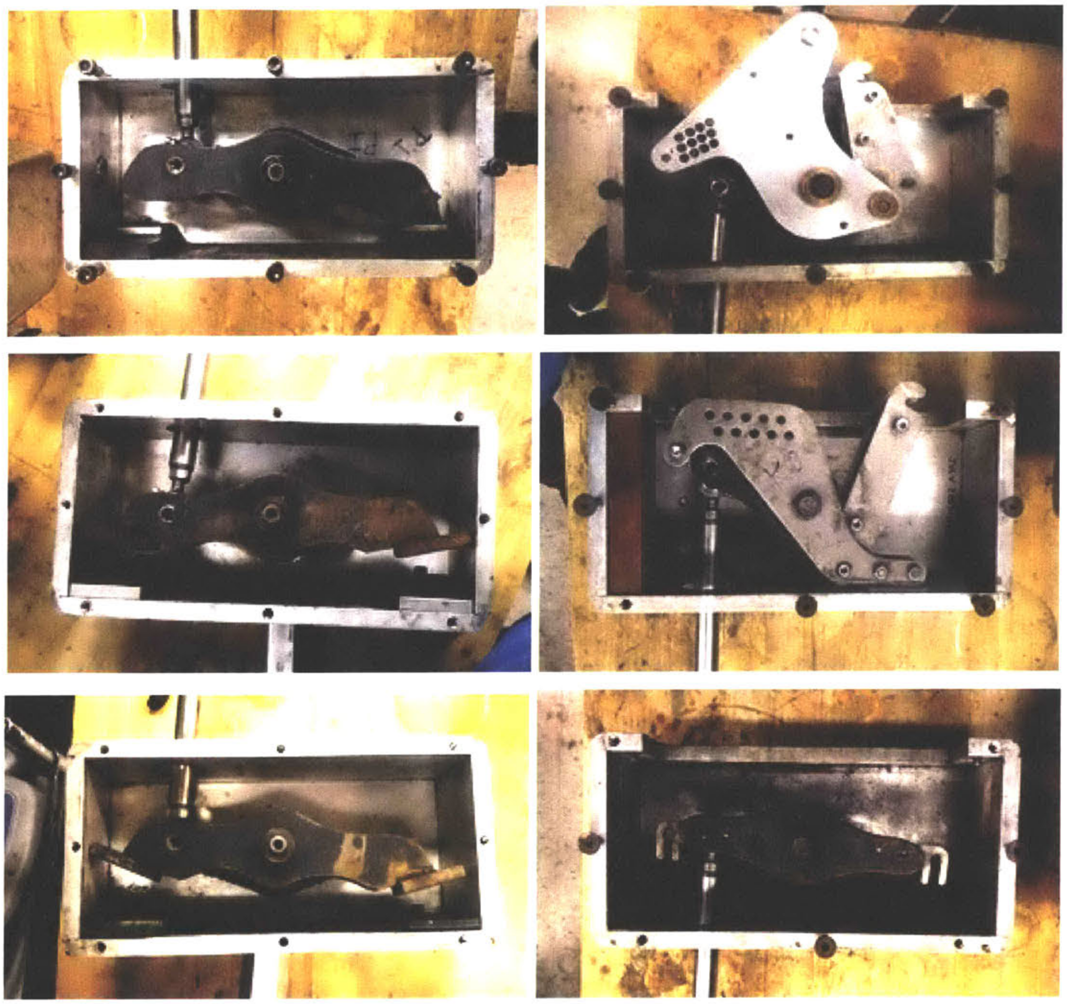

Figure 3: Current actuation systems for Pythagoras (top), Kepler (middle), and Galileo (bottom). Lower mechanisms on the left, upper mechanisms on the right.

Within each actuation system, the handle is attached to a rocker on the inside of the lower enclosure by a spline coupling (Figure 4). The handle is supported by a flange bearing on the interior, and secured by a screw on the exterior. A connecting rod is secured to one side of the rocker with a spherical rod end, transferring motion to the upper enclosure as the rocker swings back and forth. The rotation of this rocker is constrained to about 60° by two urethane end stops on the bottom of the lower enclosure (Figure 5).

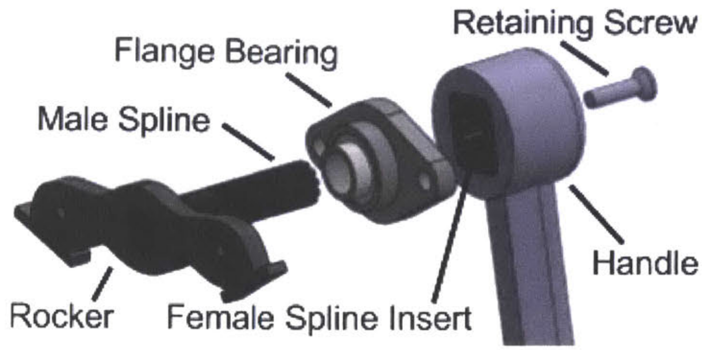

Figure 4: Exploded view of the handle attachment within the current system, lower enclosure omitted.

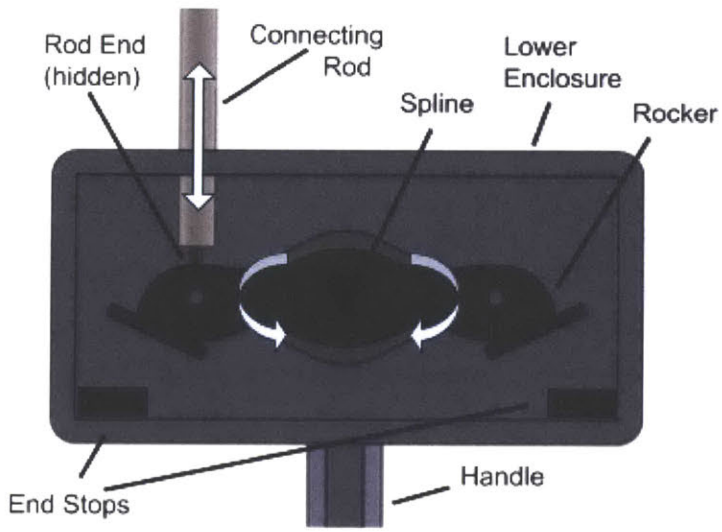

Figure 5: Motion and components within the lower enclosure.

The translational motion of the connecting rod rotates the mechanism within the upper enclosure. For Kepler and Pythagoras, this upper mechanism consists of two pairs of plates, a third, thick plate, a disk, and an extension spring (Fig. 6). The thick plate attaches to the other end of the connecting rod, and is secured up against the disk when the clutch is engaged. The thick plate is attached to the exterior plates, the disk is attached to the interior plates, and the two sets of plates are pulled together by extension spring that connects to holes in the exterior plates, and notches in the interior plates. When a high load is introduced in the system, the extension spring stretches, allowing the thick plate to disengage from the central disk, disconnecting the actuation. The thick plate is reset the on the next handle swing in the opposite direction, and motion continues.

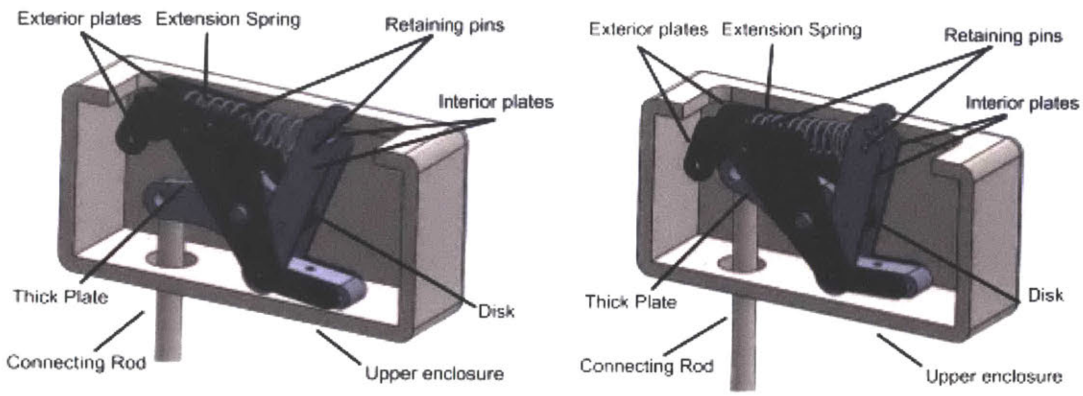

Figure 6: Kepler's upper mechanism, disengaged (left) and engaged (right).

As mentioned previously, the ceiling connectors for all three instruments vary. Despite the variance in form, the motions provided by the upper mechanisms that actuate the remainder of the system are quite similar, and are illustrated in Figure 7. With Pythagoras, a central bar holds its series of free-swinging hammers. The rotating motion of the upper mechanism torques a rod that runs across the ceiling, horizontally translating the central bar and causing the hammers to swing and strike the bells. For Kepler, the instrument is struck by a hammer that is raised by a ratcheting pawl and released at the top. This ratcheting motion is created as a result of a chain connected to one side of the upper mechanism on the platform. When the mechanism rotates, it pulls down the chain with each full swing. In Galileo, a small plate with a hook is fastened to each side of the upper mechanism rocker. A wire loops around each hook, and the two wires are pulled in an alternating fashion with the rotation of the rocker. These wires run across the ceiling and shake the metal sheet back and forth with the reciprocating motion of the rocker.

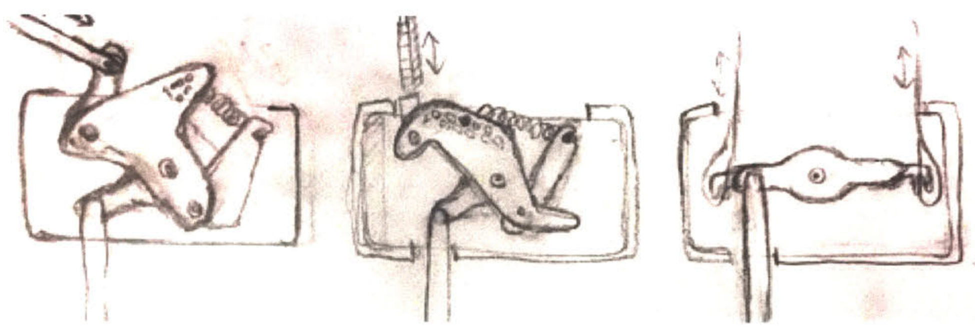

Figure 7: Ceiling connectors for Pythagoras, Kepler, and Galileo (left to right)

2.2 Mechanical Problems in the Original Actuation Design

There are three main failure points within the platform actuation system: the handle attachment to the lower enclosure, the spherical rod ends that connect the two enclosures, and, in the case of Kepler and Pythagoras, the main plate for the upper mechanism (Figure 8). The connections at these points exhibit a mixture of plastic deformation resulting from overloading of components and fracture from fatigue.

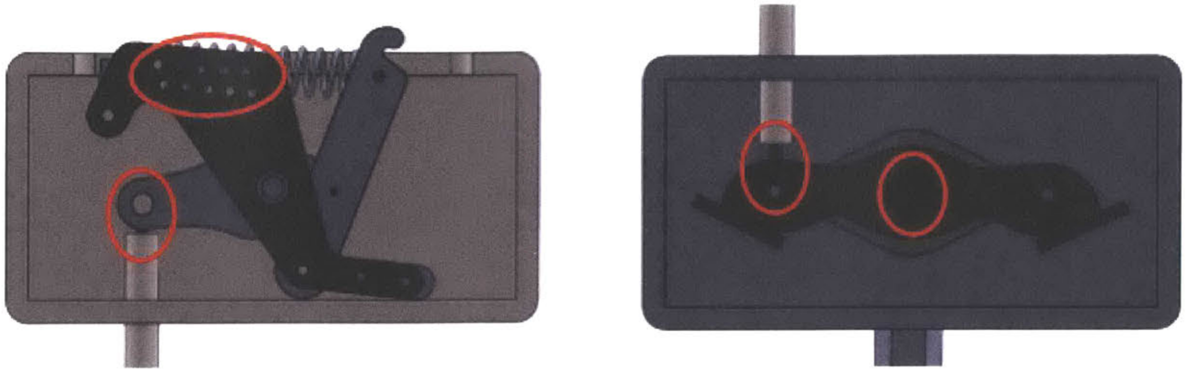

Figure 8: Failure points within the current actuation system, circled in red.

Handle Attachment

As illustrated in Figure 4 and depicted in Figure 9, the actuation handle has a female spline coupling integrated into its housing that aligns with a male spline on the assembly side in order to transmit the rotational movement of the handle to the bottom assembly. In addition, the handle is constrained from linear movement by a screw on the exterior of the handle (Fig. 9). The coupling interface has worn down and deformed with time, and the extent of the wear in the interface may be attributed to the fabrication process for the assembly. The female coupling was cut down and welded into the handle housing, and the heat from the welding process may have reduced the yield strength of the interface. The weakened material plastically deformed over time, creating the backlash, or play, in the interface. The extraneous movement created a situation in which a small portion of the torque that would have been transmitted to the lower mechanism instead gets transmitted to the exterior screw, gradually turning the screw and loosening handle.

Figure 9: Female spline coupling within handle (left), male spline coupling protruding from lower enclosure (center), retaining screw for handle (right). Wear can be seen upon the female and male halves of the coupling.

Rod End Connectors

The upper and lower mechanisms are joined by a two foot connecting rod. On each side, the rod is connected to a thick plate by spherical rod ends (Figure 5), selected to accommodate angular offsets due to the uneven surfaces of the walls of the station. These spherical rod ends within the sculpture have a tendency to fracture along the threads — a result of fatigue amplified by the stress concentration within the threads.

Top Assembly Plate

As described previously, the upper mechanisms for Pythagoras and Kepler have an integrated clutch to relieve excess load in the system. This clutch is tensioned by an extension spring, attached to the mechanism by two retaining rods that interface with holes and notches within the two interior plates of the mechanism, as seen in Figure 10. On multiple occasions, an exterior plate has fractured at the interface between the plate and the retaining rod that attaches the spring (Fig. 10). This is a result of fatigue induced by multiple cycles of loading from the spring, amplified by the concentration of stress from the rows of holes on the exterior plates. When an exterior plate fractures, the thick plate can no longer engage with the remainder of the mechanism, failing to transmit the actuation from the handle.

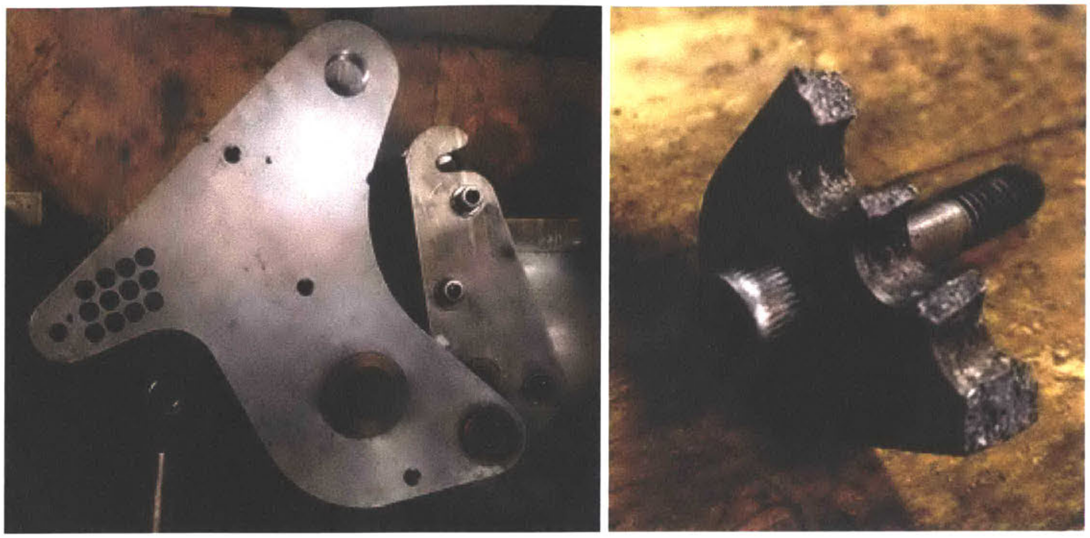

Figure 10: Upper-enclosure mechanism for Pythagoras (left; missing: retaining rods) and a fragment of its exterior plate (right).

Summary of Mechanical Design Needs

Overall, the mechanisms and linkages within the original actuation system were designed to handle high loads, but overload and fatigue caused several components to fail due to unnoticed aspects of the design. In addition, the mechanics of the system, namely the handle attachment and the relative complexity of the upper mechanisms, increased both the frequency and difficulty of maintenance. A new system needs to be created that incorporates overload protection as before, while using stronger components and avoiding geometries that generate high concentrations of stress. At the same time, this new system can be designed in a manner that decreases the maintenance requirements of the actuation portion of the sculpture.

Redesigned Actuation System

1. Design Priorities

Throughout the design of the new actuation system, durability was the primary criterion that drove design choices. An improved design must be able to withstand unexpected loads without damage to the system, specifically forces exerted upon the handle or connecting rod by passengers. In addition, critical components of the design must be resistant to wear and fatigue to promote longevity of the sculpture. As a result, the design should incorporate a mechanism within the linkage system that acts as a clutch, disengaging before the system exceeds loads that could result in plastic deformation or fatigue, along with rod shaft couplings that are robust enough to withstand forceful operation from intoxicated patrons of the MBTA.

All of these needs have been incorporated into the new design. In addition, the new design includes a modular attachment piece for the ceiling connections, so that one system can be used for all three instruments, simplifying the design, fabrication, and repair of the actuation system.

2. Mechanical Design Details

Three specific design features improve the overall durability of the actuation system (Fig. 11). The first is a new handle attachment, designed to withstand twice the expected maximum force an adult can exert. Second, a Maxwell kinematic coupling that was modified with ball detents in order to act as an overload clutch, relieving excess load in the system. Third, the pre-existing spherical rod end connectors have been swapped for a high-strength model, capable of handling 51% more radial load than before. In addition, the mechanism within the upper enclosure has been redesigned to incorporate connection points for all three instruments, simplifying the overall actuation design. These design features are described in the following sections, with key calculations for the designs outlined later on.

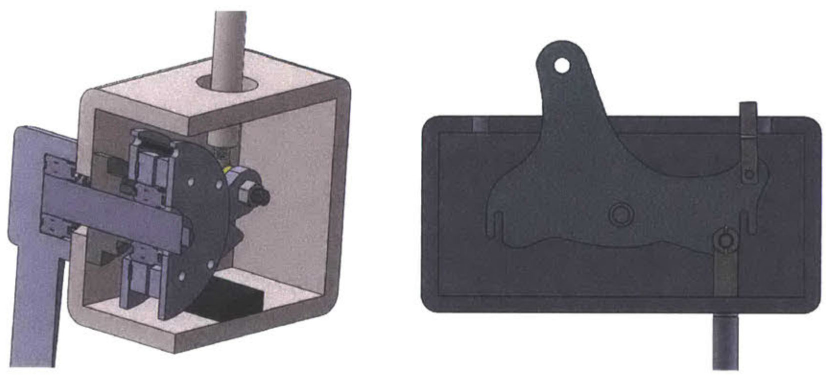

Figure 11: New actuation system, lower (left, split view) and upper (right) assemblies

2.1 Handle Assembly

The actuation system needs to be able to withstand all of the passengers' use and abuse. The most accessible part, the handle and its interfaces, needs to be particularly robust. At a minimum, the handle interface should remain intact when faced with an input force of 130 lbs, the maximum pulling force a human can exert [5], along with an estimated radial load of 300 lbf, which could easily be imparted by a large adult swinging on the handle. The new handle attachment differs from the previous in two main ways in order to meet this standard: the axial attachment is internal, as opposed to the external retaining screw, and welding has been eliminated from the fabrication process entirely. In its place, two keyless bushings are used to join the handle to the lower mechanism along a shaft--one bushing sits within the center of the kinematic coupling, the other fastens to the interior of the handle (Fig. 12), modified to accommodate the geometry of the bushing (Fig. 13). Each bushing provides a torque capacity of 334 ft-lbs, just above the largest torque expected from the 15" lever arm of the handle. In addition, the bushing within the coupling aligns with the edge of the supporting flange bearing, constraining axial movement of the handle.

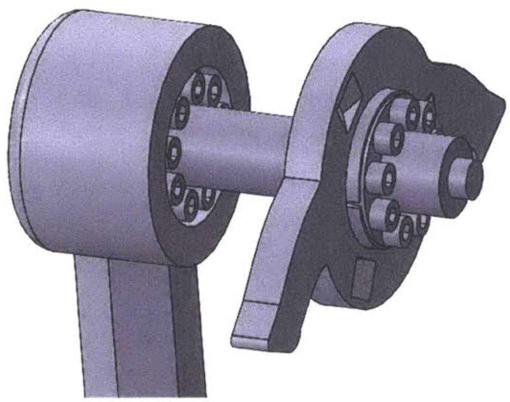

Figure 12: Handle attachment with keyless bushings

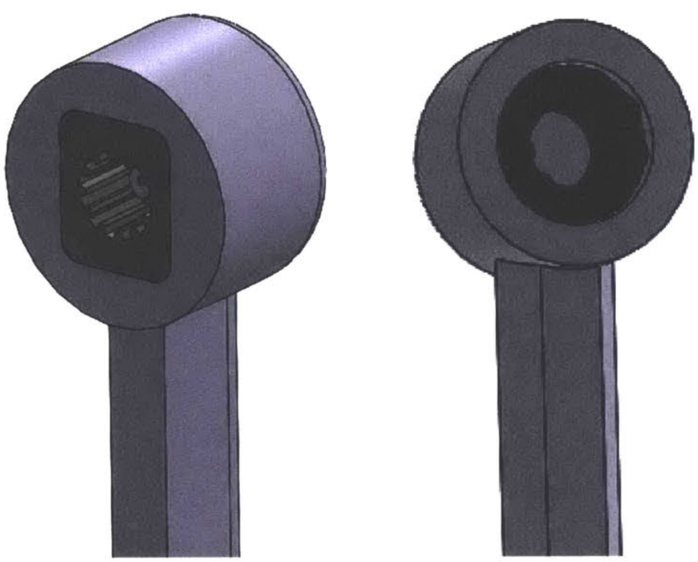

Figure 13: Current handle with spline insert (left); Modified handle with bushing (right).

2.2 Overload Protection

When a passenger "plays" one of the instruments, the handle rotation is physically constrained by two urethane end stops that engage with the lower mechanism. As a result, the torque in the lower mechanism is generally pretty low--all that is required is about 2 inch-pounds, the minimum torque needed to hold the mechanism in place at the extent of the swing. However, an unusual load is occasionally introduced into the system--either a mechanical bind, or a passenger applying a force in an unintended manner. The kinematic ball-detent coupling integrates overload prevention into the lower enclosure, protecting the components from damage in these scenarios. As seen in Figure 14, the coupling replaces the standard rounded protrusions of a kinematic coupling with spring-loaded ball-detents, such that the coupling disengages when the localized torque has reached a value equivalent to 15 lbf at the handle, just above the level of force one can comfortably exert with their arm [6]. This mechanism serves to relieve loads before they could contribute to fatigue or wear in the system.

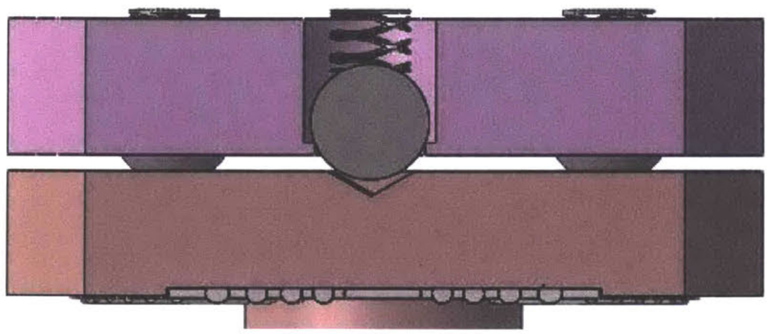

Figure 14: Grooved plate (top left), ball-detent plate (top right), and cross section (bottom) of the kinematic ball-detent coupling.

The kinematic ball-detent coupling is made up of four plates: two thick interior plates that create the coupling interface, and two exterior plates that secure the coupling together (Fig. 15). On one side, three ball detents are composed of a ball that sits in a channel, protruding out from the surface of the coupling and constrained within by a high stiffness compression spring, These detents are paired with three grooves arranged in a radially symmetric fashion on the other plate (Fig. 16). Two thinner plates fastened with screws and standoffs surround the grooved and ball-detent plates, constraining the axial positioning of the coupling interface. The mechanism operates by disengaging the coupling interface when the work done by the torque in the coupling overcomes the potential energy of the spring force within the ball detent, removing the ball from the groove.

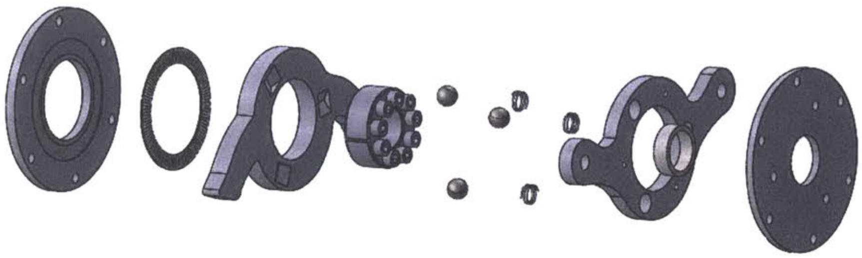

Figure 15: Kinematic ball-detent coupling assembly

As mentioned earlier, the grooved plate is fastened to one of the keyless bushing, transmitting torque from the handle. Since the grooved plate is coupled to the handle, and the ball-detent plate is coupled to the remainder of the linkage, a thrust bearing sits between the grooved plate and its exterior plate in order to enable the two plates to slide freely. In addition, two "arms" protrude from the sides of each thick plate. The arms on the grooved plate engage with the end stops to limit the handle rotation. The arms on the ball-detent plate have a through hole to engage with the spherical rod ends. A full assembly of the lower enclosure can be seen in Figure 16.

Figure 16: Lower enclosure, full assembly, screws missing.

2.3 Rod Connectors

The walls within the Kendall/MIT station are not straight. As a result, there is a significant angular offset between the upper and lower enclosures for several of the actuation stands on the platform. Despite the failure of the screw threads in the previous actuation system, spherical rod ends remain the most appropriate joint to accommodate the lopsided geometry of the linkage. Consequently, spherical rod ends were used in the new design as well, but with two modifications. First, the overload threshold was set below the load equivalent to the endurance limit of the rod ends, drastically reducing the potential for fatigue. Second, the standard spherical rod ends were replaced with McMaster's high-strength equivalent, increasing the radial load capacity by 51%.

2.4 Upper Enclosure

The relocation of the overload protection into the bottom assembly freed up an entire enclosure in the design. This free space has been utilized to standardize the actuation system. Inside the upper enclosure, a new, oblong rocker has been designed with attachment points for all three styles of ceiling connectors. The rocker, seen below (Fig. 17), includes a pair of hooks for Galileo, a through hole for Pythagoras, and a clevis for Kepler's chain attachment, all within one plate. These attachments points were designed to mimic the orientations and placement points from each original design. For Galileo, the current wire length could be modified rather easily, so the new design preserves only the spacing and symmetry of the two hook attachments. For Kepler, the exact horizontal and vertical displacements from the rotational axis to the connection point were preserved. For Pythagoras , the radial distance between the attachment through-hole and the rotational axis of the rocker remained constant in order to preserve the geometry for the torque Pythagoras provides to its ceiling connector.

Figure 17: Modular connecting plate

3. Designing for Overload

When torque is applied to one half of the coupling, two displacements occur simultaneously: an angular displacement between the two plates of the coupling, and an axial displacement between the ball and the face of the grooved plate. The torque produces work with the angular displacement, and the energy from that work is converted into potential energy in the spring, generated by the axial displacement of the ball. Three basic equations can be combined to establish the relationship between the spring force and the required force to disengage the coupling,

$$PE_{spring} = 1/2ky^2 \qquad \text{Eq. 1}$$

$$W = F \times x \qquad \text{Eq. 2}$$

$$tan(\theta) = y/x \qquad \text{Eq. 3}$$

where Eq. 1 is the potential energy of a displaced spring, Eq. 2 is the work-energy equation, and Eq. 3 is the geometric relationship between the opposite and adjacent sides of a triangle. In addition, the torque in the coupling is divided between the three ball detects. As a result, combining these three equations results in the relationship between the spring constant for each spring and the overall torque in the coupling (Eq. 4),

$$T_{coupling} = \frac{3}{2}\, k \cdot y \cdot \tan(\theta) \cdot r \qquad \text{Eq. 4}$$

where "r" is the radial offset of the ball detents. The angular displacement between the two plates, alpha, has been approximated as the translational displacement of the ball in the groove, x, due to the small degree of angular displacement (Figure 18).

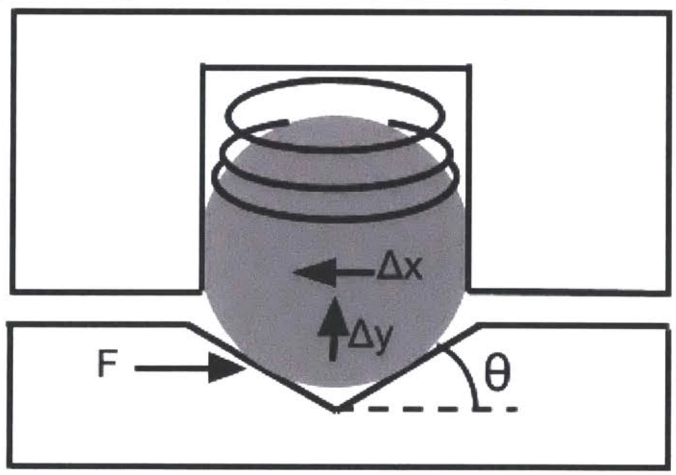

Figure 18: Diagram of the ball and groove displacement

In order to maximize the disengagement torque and minimize the size of the coupling, the radial offset was set to 1", and the axial displacement was set to 0.1". In addition, the groove angle was set as 45 degrees for ease of fabrication.

Selection of Overload Torque Level

The ball-detent kinematic coupling was designed such that the interface decouples at a torque level that was above the standard operating range, but well below a level that could be damaging to components within the system. Given that the operational force is only 2 lbf, functional, 12 lbf, the maximum pushing force a human can comfortably exert [6], was selected as an initial reference point. Adding a small margin such that the coupling doesn't engage during standard operation, an overload torque threshold of 225 inch-lbs was selected, corresponding to an input of 15 lbf.

Compression Spring Selection

Given the desired decoupling threshold of 15 lbf and Eq. 4, the required individual spring stiffness was 200 inch-lbf. In addition, this spring needed to have an outer diameter less than 0.625", and an overall length of 0.30" +/- 0.05". A spring with these exact properties and dimensions could have been used, or a longer, weaker spring could have been cut down according to the stiffness relationship in Eq. 5 [7],

$$k=AE/L$$

where A is the cross-sectional area, E is the Young's modulus, and L is the length. This relationship means that any spring could have been modified as long as the stiffness times the length equated to 200 lbf. For a relatively small spring, 200 inch-lbf is a very high stiffness, so a 50 inch-lbf 4" spring was cut to size to achieve the desired properties.

Kinematic Coupling Design Verification

The primary goal of the new actuation system is to reduce the chance that a part will fail, and the new design focuses on utilizing the kinematic ball-detent coupling as the sole source of overload relief in the system. A simplified version of the coupling was fabricated and load-tested in order to verify that the mechanism functions as intended. This design verification and testing is outlined in the following sections.

1. Fabrication of Simplified Coupling

The kinematic coupling design was simplified for initial testing purposes, preserving the majority of the detailed coupling interface. As you can see in Figure 19, the simplified design incorporates the two thick plates and two thin plates from the original design. The four main plates were machined out of 6061 aluminum on a CNC mill, with socket head cap screws and standoffs used to fasten the bulk of the assembly.

Differences between the new and simplified design include the plate shape, fastener arrangement, and spring stiffness. The most apparent differences are the square shape used for the four plates, and the handle, that is now half as long and protrudes from the grooved plate of the coupling. The plate shape was designed for ease of fabrication and mounting, and the handle was designed to half of the length of the original. The clamping force for the coupling is provided by the ball-detent plate, as opposed to the the back plate. In addition, complications during fabrication resulted in modification to the spring stiffness-- the chosen ball-detent springs were more difficult to modify in a precise and accurate manner than anticipated, so weaker, poly-wave disc springs of the appropriate geometry were used in their place for testing purposes.

The changes in plate shape, handle arrangement, and fastener placement should have no effect on the test setup. In contrast, the resulting input force was decreased by the change in stiffness. That being said, the results can be compared to the expected force threshold as calculated based upon equation 4 to compensate for the expected effects of these changes.

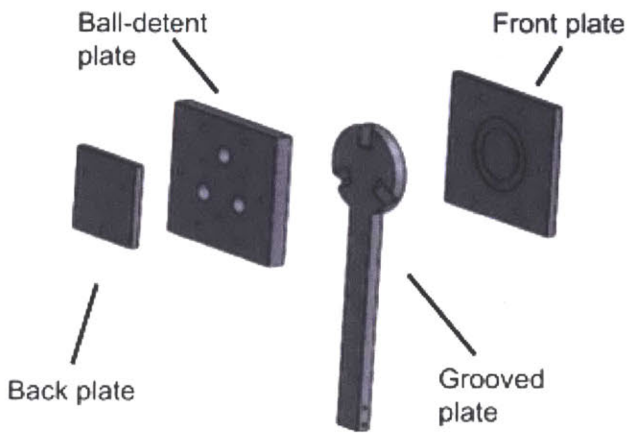

Figure 19: Simplified coupling assembly (fasteners, springs, and balls omitted)

2. Apparatus and Testing

The stress relief testing was performed on the simplified coupling interface by recording the load applied to and linear displacement of the coupling arm with an Instron Universal Testing System (Fig. 20). The apparatus was constrained to a table with two C-clamps, positioned such that the Instron load point was located 8.5" +/- 0.5" away from the center of rotation. Five trials were performed during which the Instron arm displaced the coupling arm until the ball had fully disengaged from the groove, collecting position [mm] and load [N] data at 32 samples per second. The coupling was reset and the load reading was zoroed before the start of each trial.

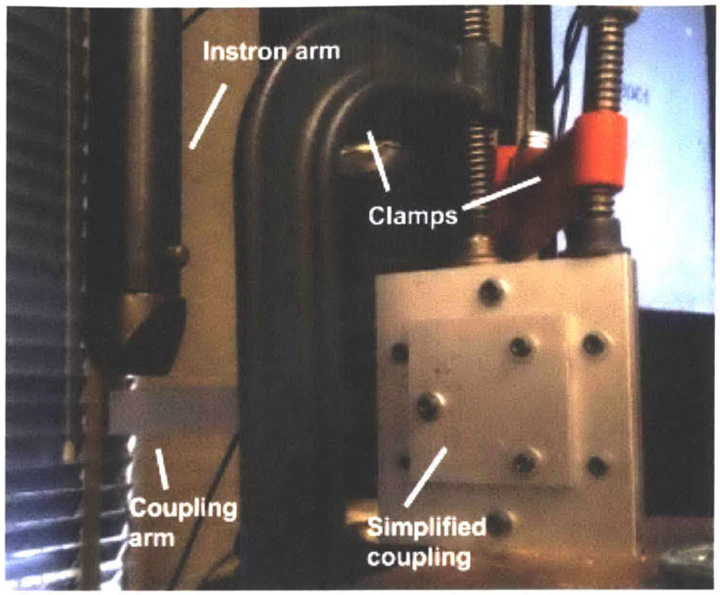

Figure 20: The stress relief test apparatus, including the simplified coupling, and the Instron testing system

3. Results and Discussion

Load and position data were imported into MATLAB for analysis, illustrated in Figure 21. In all cases, the input force with respect to displacement rose at an increasing rate, then dropped off suddenly, a marker that coincided with the disengagement of the coupling. The maximum force preceding the drop-off can be taken as the overload force value. The test setup was performed with a collective spring stiffness of 200lbs/in, corresponding to an expected overload force value of 2.98 N.

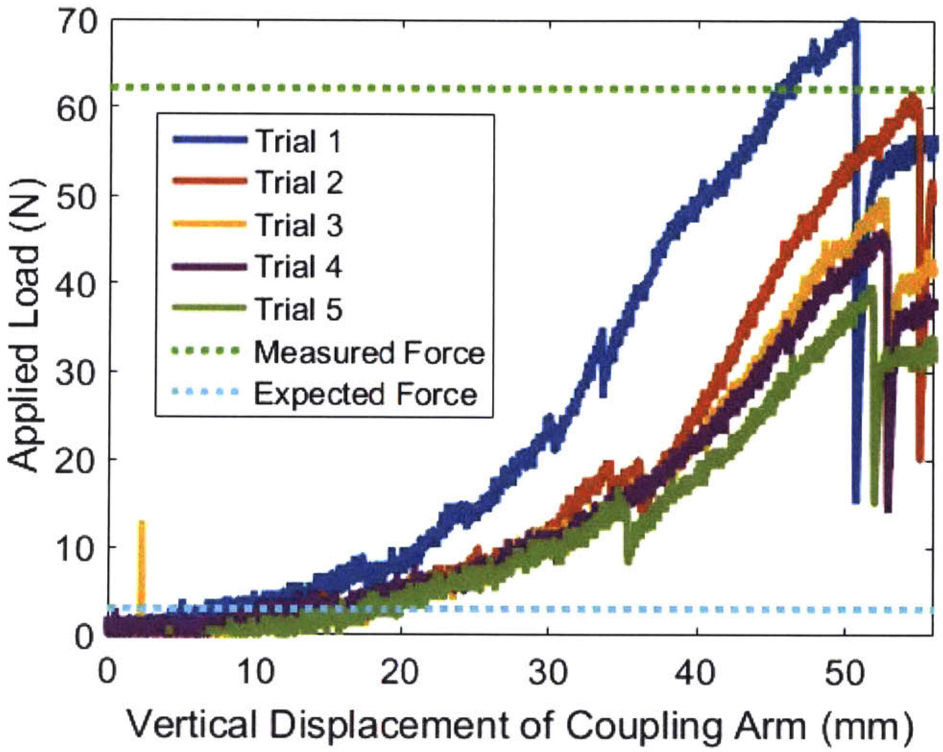

Figure 21: Input load (N) on the coupling arm as it is displaced. Average measured overload force is 62.2 N, twenty times higher than expected.

Across five trials, the average force was 62.2 N, approximately 20 times greater than expected. This large difference can be partially attributed to experimental error, given that the tightening of the standoffs in the assembly was performed by hand, and may have resulted in a non-trivial amount of preload on the springs. In addition, the force threshold decreased unexpectedly at a rate of approximately 3.5N per trial. The geometry of the poly-wave disc springs used caused some deformation during testing, which could explain this decrease to a degree, and, while the geometry of standard compression springs should alleviate this issue, this occurrence brings to attention the need to assess the rate of wear and degradation of the springs over time.

Conclusion and Future Work

The new actuation system incorporates many changes that should have a significant impact upon the longevity of the Kendall Band. The standardization of the system makes it easier to debug and replace components. Similarly, the relocation of the overload protection into the lower enclosure makes the components that are more likely to fail more accessible.

The results of the stress testing upon the simplified coupling design, while quite different than expected, demonstrated that the overload protection can function as desired with some modifications. During the fabrication of the simplified coupling interface, it quickly became apparent that springs can be quite difficult to alter in a precise, repeatable manner. Between the difficulty of modification and the mechanical properties available for most springs, a stiff elastomer may provide a better solution for the desired coupling behavior. Fortunately, the spring stiffness is a factor that is relatively simple to vary to achieve the desired threshold. In addition, the required stiffness and tolerance for the coupling can be relaxed by increasing the axial distance the ball needs to travel to disengage.

Going forward, the new design is promising, but there is more testing to do to ensure the system as a whole functions as intended. Although minimizing fatigue and wear was one of the primary design priorities, long-term durability was not emphasized within this design cycle. Further testing should be performed to characterize and compare the the effects of fatigue on the new assembly. Lastly, there is plenty of progress to be made going forward, as this design is only the first step in restoring the Kendall Band to a working state once again. And, if this restoration is to last, there is quite a bit of repair and documentation that needs to take place, but this design is an essential starting point.

References

[1] MIT Kendall Band Preservation Society, 2011, "The Kendall Band," https://kendallband.wordpress.com/about/the-kendall-band/.

[2] MIT Kendall Band Preservation Society., 2011, Kendall Band Operations Manual, Boston, MA.

[3] Daniel, M., 2007, "This Matisse seeks a patron," Boston Globe Newspaper Company.

[4] Tarkanian, T., 2016, Senior Lecturer at MIT, private communication.

[5] Tillman, B., Fitts, D. J., Woodson, W. E., Rose-Sundholm, R., and Tillman, P., 2016, Human Factors and Ergonomics Design Handbook, Third Edition., McGraw-Hill Education, USA, pp.651.

[6] Tanaka, H., 2011,"Comfortable Pushing/Pulling Force Exertion for the Design of Consumer Products", Biometrics and Kansei Engineering (ICBAKE).

[7] Budynas, R., 2015, Shigley's Mechanical engineering Design, 10th Edition., McGraw-Hill Education, USA.

Appendix A: Bill of Materials- New Actuation Design

Purchased Parts

Item (Part # if applicable)	Source	Quantity
Thrust Bearing (35TY02)	Grainger	1
Keyless Bushings (C200E-100)	Climax Metal Products	2
1/2" 10-32 Socket head cap screws	McMaster	12
3/8" 10-32 Socket head cap screws	McMaster	3
Standoffs (91125A469)	McMaster	6
1/2" Steel Balls (9529K22)	McMaster	3
Compression Springs	McMaster	1
High-Strength Rod Ends (60745K241)	McMaster	2
3/8" Shoulder Screws (91273A313)	McMaster	2

New Custom Fabricated Parts*

Name	Part Code	Material	Quantity
Grooved Plate	NA-KC-GP	Steel	1
Ball-Detent Plate	NA-KC-BDP	Aluminum	1
Front Plate	NA-KC-FP	Aluminum	1
Back Plate	NA-KC-BP	Aluminum	1
Lower Enclosure Shaft	NA-LE-S	Steel	1
Modular Rocker	NA-UE-MR	Aluminum	1
Kepler Ceiling Adapter	NA-UE-KA	Aluminum	1

*For CAD files and part drawings, contact the author at marackah@gmail.com

Pre-existing Fabricated Parts**

Item	Part #	Quantity

Upper Enclosure	PI-T-03	1
Lower Enclosure	PI-H-06	1
Flange Bearing	PI-H-08/NTN FL205J	1
Connecting Rod	PI-B-01	1
Frame Bearing	PI-T-11	3
Lower engraved mounting plate	PI-H-01	1
Mounting plate	PI-T02	1
Assorted mounting fasteners	PI-T-04/PI-H-07	13
Handle (Modified)	PI-H-13	1
Urethane End Stops	PI-H-09	2

**Part drawings can be found in the Kendall Band Operations Manual [2]; Pythagoras-specific part names were listed for reference.