Design and Testing of a Motion Controlled Gait Enhancing Mobile Shoe (GEMS) for Rehabilitation

by

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Abstract

Persons suffering central nervous system damage, such as a stroke, coma patients, or individuals that have suffered damage to the spinal cord, brainstem, cerebellum, and motor cortex, sometimes develop an asymmetric walking pattern where one leg does not fully swing backward. This uneven gait hinders these individuals in properly and efficiently moving through everyday life.

Previous research in humans and various animals has introduced a split belt treadmill to analyze possible rehabilitation, which can recreate a correct gait pattern by altering the speed of each track. Gait adaptation was achieved by having the split belt treadmill move each leg at a different velocity relative to the ground and thus forcing a symmetric gait. Test subjects' gait would adapt to the speeds and a normal gait pattern could be conditioned while on the split belt treadmill. However, after short trials, individuals were unable to neurologically store these feed-forward walking patterns once walking over ground. Also, test subjects would have difficulty adapting their learned walking gait over different walking environments.

The gait enhancing mobile shoe (GEMS) makes it possible to adjust an asymmetric walking gait so that both legs move at a relatively symmetric speed over ground. It alters the wearers walking gait by forcing each foot backwards during the stance phase, operating solely by mechanical motion, transferring the wearer's downward force into a horizontal backwards motion. Recreating the split belt treadmill effect over

ground by using the GEMS will potentially enable me to test the long term effects of a corrected gait, which is impossible using a split belt treadmill.

A previous prototype of the GEMS [1] successfully generated a split belt treadmill walking pattern, but had various drawbacks, such as variable motion from step to step. My new design of this rehabilitation shoe promises to alter the user's gait as a split belt treadmill does, and to be mechanically stable operating without any external power sources.

I designed and constructed a new motion controlled gait enhancing mobile shoe that improves the previous version's drawbacks. While mimicking the asymmetric gait motion experienced on a split-belt treadmill, this version of the GEMS has motion that is continuous, smooth, and regulated with on-board electronics. An interesting aspect of this new design is the Archimedean spiral wheel shape that redirects the wearer's downward force into a horizontal backward motion. The design is passive and does not utilize any motors and actuators. Its motion is only regulated by a small magnetic particle brake. Initial tests show the shoe operates as desired, but further experimentation is needed to evaluate the long-term after-effects.

Chapter 1 : Introduction

1.1 : Project Motivation

While walking all healthy humans have a relatively similar walking pattern (gait). Each leg performs the same movements in a cycle 180 degrees out of sync from each other; this repetition of leg and foot movements is called the gait cycle. It involves two parts, or one stride, and it is divided into the stance phase and the swing phase. The stance phase is the period during which the foot is in contact with the ground and the swing phase is the period of the gait cycle when the foot is swinging forward.

Stroke patients [2], coma patients, and/or people with central nervous system damage [3, 2, 4] sometimes develop an asymmetric walking gait, preventing them from moveing around normally in everyday life. Such individuals are unable to continuously perform a correct symmetric gait cycle. In these hemiplegic patients, one leg lags the other, not traveling far enough backwards to effectively push the individual forward during walking. This handicap creates an asymmetry that can result in a worsening asymmetry [22] and so strains the individual's healthy limb.

Studies, where the strategies used on hemiplegic subjects to adapt their walking pattern to a velocity-dependent resistance applied against hip and knee movements, showed there are two basic ways the human body alters its normal walking gait [3]. One is by a feedback driven, or reactive adaptation that occurs in response to a sudden external perturbation. This type of gait adaptation does not require any previous training. The second is a feed-forward driven adaptation [3], where training is required to neurologically store certain movement patterns into muscle memory. This type of gait conditioning produces longer aftereffects.

It was shown that using a split belt treadmill with asymmetric belt speed velocity ratios [4, 2, 5] allowed individuals to adapt their walking gait to the asymmetric belt speeds showing trained aftereffects. When the split belt treadmill is returned back to a 1:1 ratio, the individual walked with a trained and altered gait. This altered walking pattern, however, vanishes after a short period of time walking on a 1:1 ratio split belt treadmill or over ground and the individual's initial asymmetric walking gait is regained. This type of gait alteration is a feed-forward gait adaptation. Riesman et al. [2] suggest that long term effects need to be studied in real world situations. These long term effects of correcting an asymmetric gait can better be achieved with a mobile shoe, which a test subject would wear for an extensive period of time in multiple environments.

This concept has evolved into the Gait Enhancing Mobile Shoe (GEMS). The portable GEMS imitates the same relative foot motion experienced in previous split-belt treadmill gait rehabilitation methods, but while walking over ground. In other words, as one leg travels one complete step, the other leg only covers a fraction of the distance covered by the first leg, hence, mimicking an asymmetric split-belt treadmill.

Other advantages of such a portable rehabilitation device are that it can be worn in different environments including one's own home and also that it can be worn for an extended period of time, thus the corrected gait is predicted to persist longer than the gait correction from a split-belt treadmill. Moreover, the ability to wear the GEMS for longer periods of time increases the probability of producing positive gait rehabilitation effects.

There are two basic ways the GEMS rehabilitates asymmetric walking patterns. The first method utilized by the GEMS corrects an asymmetric gait by letting the test subject wear the shoe on the strong leg making it swing back past the stance phase and letting the individual toe off (push off) with that leg. In a way it hinders full forward progression of the healthy leg as a slippery or icy surface would do. As a result both legs will propagate the individual forward by similar distances. This is compensation, but no permanent rehabilitation will come from this method. However, this compensation method will assist individuals to walk with a symmetric gait.

The second method is letting individual wear the shoe on the weak leg and so limiting the forward motion of the weak leg. This motivates the individual to lengthen the forward distance to the point where the initial heel contact position would be. The GEMS also pushes the leg backwards forcing the weak leg to toe off properly and so recreating a normal gait.

Considering past hemiplegic research, it is hypothesized that prolonged wearing of the GEMS will have positive after-effects helping individuals with asymmetric walking patterns adapt a more normal walking gait when wearing the GEMS over a longer period.

1.2 : Design Goals

It is my intention to create a device that adds to the rehabilitation concept previously outlined in section 1.1. In general terms, it is my intention to construct a mobile shoe that mimics the kinematics of past split-belt research while eliminating the context awareness problem during gait adaptation.

Unlike the previous GEMS, this model is to be fully motion controlled in order to make it more versatile to various subjects and walking conditions. While the previous model was solely based on a mechanical design, the new design is going to utilize electrical components to control and regulate the motion of the shoe. The new version of the GEMS is controlled by an on-board microprocessor. This microprocessor takes inputs from an accelerometer and potentiometer to recognize where in the gait cycle the GEMS is located. This microprocessor also will regulate the resistance of the shoe as it pushes the user's foot backwards using a small magnetic particle brake which restricts wheel rotation and a gear train that reduces the input torque from the wheels to the brake. All the electrical components are to be powered by a battery pack worn around the waist. Below are the ultimate design requirements for the GEMS.

1. *Total weight:* The total weight of the shoe should be no more than 2.2lb (1 kg), which is only slightly more than a typical tennis shoe, which weighs roughly1.65lb (0.75 kg). The first prototype weighs 2.43lb (1.1 kg) and could easily have some of the weight in the frame reduced. The second prototype weighs 4.4lb (2 kg), which will need significant optimization in order to reduce the weight to the desired amount.

2. *Strength:* The shoe should be capable of fully supporting the dynamic forces from a 115 kg person. This means a 115 kg wearer can stand or walk on it without failure. This does not mean that the shoe can stop the horizontal motion at any point prior to the toe off stage. The first prototype meets this requirement, but the second one becomes unreliable when a person weighing more than 90 kg uses the shoe.

3. *Generated motion:* The total generated horizontal difference between the motions of the two feet during stance should be at least 30 cm. This means one foot can go forward 15 cm and one foot can go backward 15 cm, which would enable a total difference of 30 cm. Both prototypes meet this requirement. The first prototype can generate a backward motion of 25-35 cm, depending on the step. The second prototype can generate a 15.2 cm motion, so with a similar shoe on the other foot it would meet this requirement.

4. *Consistent motion:* The horizontal motion generated by the shoe should be consistent on every step, at most the variability can be ±5%. It is currently unclear what amount of variability would still permit an adaptation. However, it is clear that less is better. The first prototype does not meet this requirement. In initial testing, it appears that the second prototype meets this requirement, but further testing is needed.

5. *Portability:* The shoe should be completely portable, with no external cables. If necessary, a small battery pack attached to the leg or hip would be acceptable. Both prototypes meet this requirement.

6. *Time to recharge:* The wearer should be able to walk continuously on the shoe for at least 1.5 hour. The first prototype meets this requirement. The second prototype has not been tested to this extent.

7. *Size (height):* The height of the shoe (i.e., from the ground to the bottom of the user's shoe) should be no more than 2.5" when the heel first contacts the ground.

Some height is necessary for the actual shoe components and also for redirection of forces based on a small downward motion being transferred to the required backward or forward motion. Neither prototype meets this requirement at the current time. Based on the size of the current shoes, optimizing the forces on the wheels and springs as well as determining the tolerances for the internal parts will allow this requirement to be met on future versions.

8. *Size (width):* The width of the shoe should be similar to that of a typical tennis shoe. In no case should the shoe protrude 1 inch more to the inside of the leg than a typical tennis shoe does. A protrusion of 2 inches or less to the outside of the foot is acceptable since this will not interfere with walking. Both prototypes meet this requirement.

9. *Size (length):* The length of the shoe should be similar to that of a typical tennis shoe. A longer shoe is acceptable as long as there is no interference with either the typical toe off nor heel contact events. Both prototypes meet this requirement.

10. *Cost-effectiveness:* The shoe should be cost effective to manufacture. Assuming reasonable economies of scale, the shoe should be able to be produced for less than $500. Neither of the first two prototypes meet this goal as they were both custom made and have not been optimized for manufacturing.

11. *Shoe Progression:* The GEMS should utilize a special shaped wheel. This wheel has a form of constant radius change (Archimedean Spiral). It transfers the users vertical weight into a horizontal force. This wheel shape should allow a total push distance of the shoe of at least 6.5in (15cm).

12. *Straps:* The GEMS design should have straps so a user can fasten their everyday shoe on top of it. The straps should be designed in a way to where there is minimal movement between the GEMS and the user's foot during operation.

13. *Opposite Foot Support Platform:* A platform for the opposite leg should be made to compensate to any height difference created by the GEMS between both legs. This second support platform has identical variation in dimension and weight to reduce unnecessary inconsistencies during operation of the GEMS.

1.3 : Section Overview

In the foregoing sections I will be describe a clear and complete background to the work presented in this manuscript. The background covers the kinematics and kinetics of the normal and abnormal human gait and a hemiplegic rehabilitation method used to improve gait asymmetry. The background chapter also covers a summery of the proposed gait enhancing mobile shoe concept and as it relates to context awareness. To complete the background to this project, the previous GEMS is outlined including it's abilities, strengths and weaknesses.

A detailed description of my project's design and assembly, is outlined in Chapter 3 of this manuscript. This design and assembly Chapter explains the individual components of the GEMS, their relevance in a global view of the project, and their detailed setup and layout.

In Chapter 4 the results of the project is presented in comparison to the initial design goals presented in Section 1.3. Each criteria is weighted against the resulting valued obtained by the new GEMS design.

While this project shows promising results, room for future improvement and optimization is plentiful. The future work chapter discretely describes each area of improvement and elaborates on future possibilities.

Chapter 2 : Background

2.1 : Human Walking Gait

It is important to describe the kinematics and other details of normal human gait before discussing the applications of the GEMS and its rehabilitation methods. Walking is an innate human ability to propel one's body forwards or backwards. A healthy walking pattern movement is rhythmic and symmetric in nature with a constant velocity forward progression. The forward and backward walking motions are exactly similar in kinematics but differ in EMG activity in various leg and foot muscles [6]. For modern life, mobility through the process of walking is a crucial activity of daily life. A major abnormality such as a hemiplegic gait can greatly hinder an individual to efficiently go through the process of everyday activities. A scientific poll has shown walking to be the most significant ability during recovery in stroke patients [23].

The kinematics of the human gait cycle can be divided into two distinct phases: The stance phase and the swing phase [7]. Furthermore, these two gait cycle phases can be broken down into seven gait cycle instances shown in Figure 1. When walking, these gait cycle sub-phases are exactly mirrored 180 degrees out of phase for each leg.

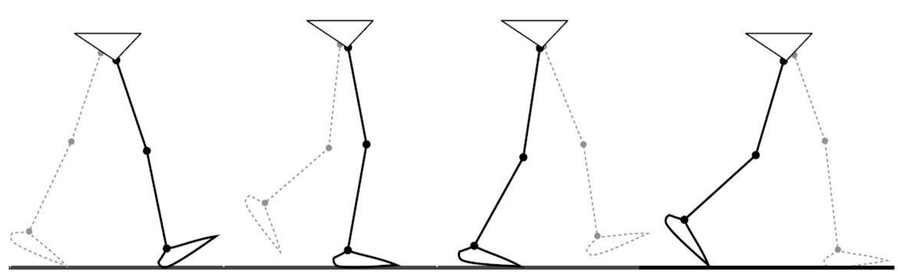

Figure 1: Adult human walking gait cycle

Although the human gait has the same characteristics in all healthy individuals, there are slight variations in this gait in every individual. Variations in healthy human gait stems from the fact that each individual learns this pattern early in life [24]. It is also universally known that many different variables affect the walking pattern of an individual; such variables include but are not limited to shoe cushioning, shoe height, shoe weight, or a person's psychological mood. In addition to factors previously listed, individual's skeletal and muscular variations also account for variation in gait. Even though there is an average human gait to describe the details about the pattern, everyone has their own variation in walking.

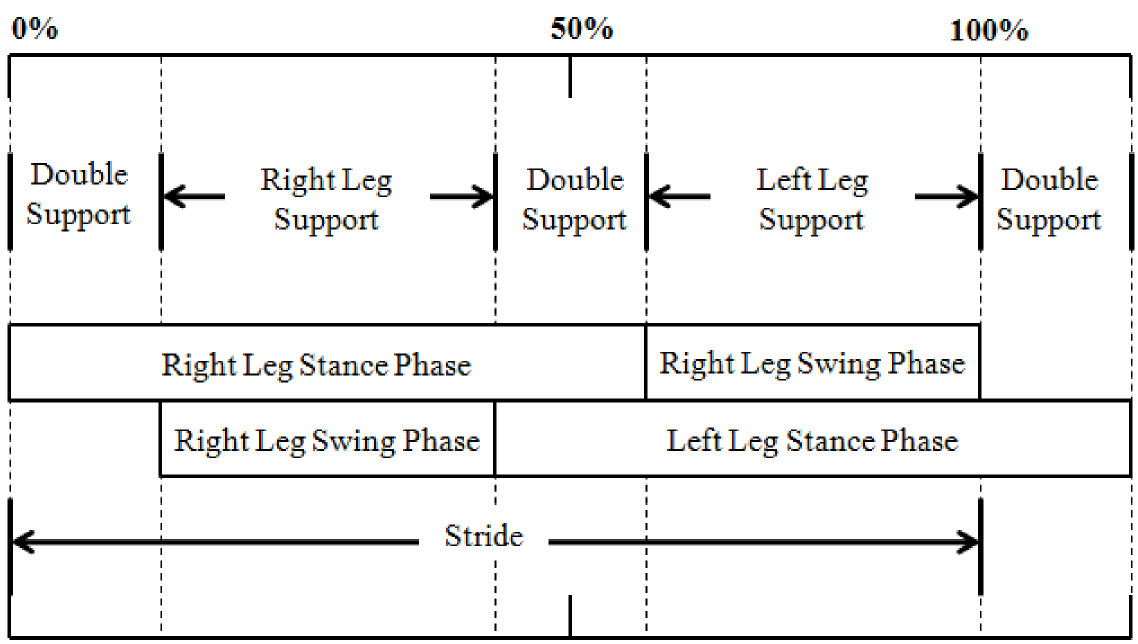

Figure 2: Time duration for each leg in gait cycle

Figure 2 shows the time spent by each foot in stance and swing phase. Notice that there is a time where both feet are contacting the ground at the same time; this is referred as "Double Support". As an individual walks at a faster pace the double support time decreases and finally disappears as the individual starts running. The step length is the distance where the left heel strikes the ground to the point where the right heel strikes the ground.

Granat et al. [25] use a specially designed shoe insole with switches to divide a hemiplegic gait into subcategories. This study adds an interesting aspect of a hemiplegic gait cycle called scuffing. Scuffing is described as any foot contact during the swing phase. In other words, as the foot toes off the ground, it initiates into the swing phase. While the foot swings from this toe off toward heel contact, it makes contact with the ground.

Different gait analysis systems have been developed to further analyze human gait, these analysis tools range from motion cameras for detailed kinetic and kinematic gait analysis to custom or specialized devices for foot pressure and temporal analysis [25]. Although there are some non-technological ways such as using foot prints and stop watches, gait analysis systems which can track distance and time of the gait cycle (temporal and special gait measurements) and are categorized as follows:

- Motion Cameras – Motion cameras come in a variety and range from more than one camera capturing the same motion from different angles to form one motion picture to infrared cameras that utilize reflective nodes placed on a moving object. Examples include the “Vicon” system. [26]

Figure 3: Vicon motion camera. [27]

- Conductive mat – A simple device that itself changes electrical resistivity in order to map static forces/pressure applied to its surface. These static force or pressure is then turned into electrical signals which in turn become two dimensional pictures available for analysis

Figure 4: Conductive mat. [28]

- Resistive walkway – This type of system utilizes the change in resistivity of a resistance grid laid across the floor. As a subject walks across the floor, the system measures the change in resistance and so extracts time and distance values for the individual's gait cycle [29, 30]
- Switch Walkway – This category can be subdivided into two systems: Little switches imbedded inside the soles of a mobile shoe and switches that are distributed across a walkway. During walking as the individual activates a switch, the system can determine the timing and pressure distribution of each step. This is a relatively low cost method of determining time and distance measurements of the gait cycle.

Considering the kinetics of the gait cycle, Figure 5 shows the horizontal and vertical forces during the stance phase in an adult walking gait starting at heel contact. These reaction forces are exactly identical in both legs for a healthy human gait.

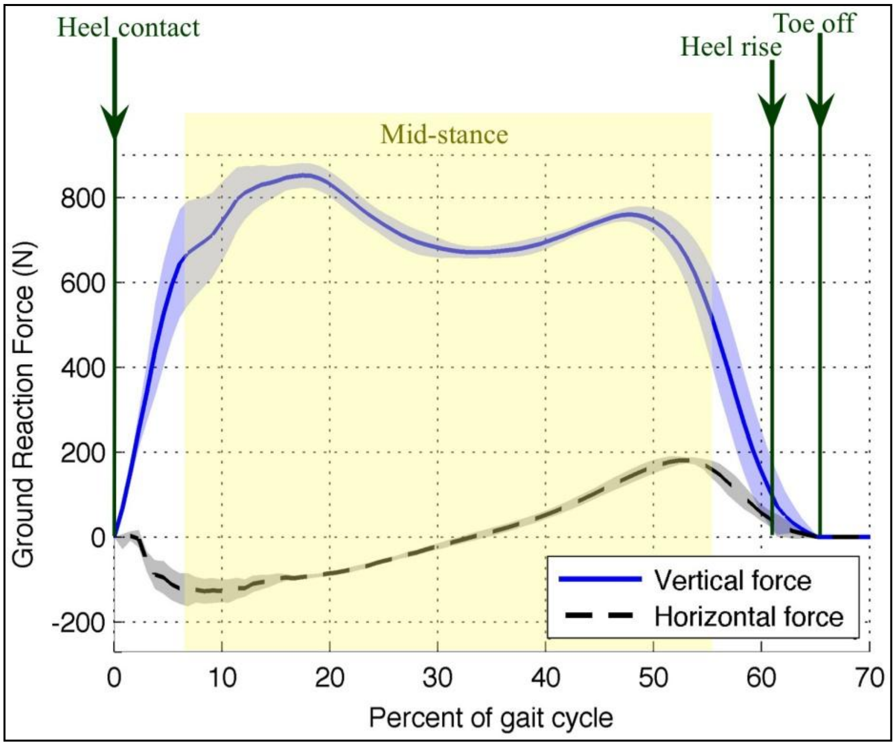

Figure 5: The horizontal (Fx) and vertical (Fz) forces change throughout the gait cycle.

The GEMS uses these changing forces to alter gait patterns for rehabilitation

Notice that during the stance phase, a slightly fluctuating 800N vertical force is applied, while horizontal reaction forces of up to ±100N are experienced. Also notice that at the 30% gait cycle mark, the horizontal reaction force switches from pushing the leg backward to pushing the leg forward. This shows that the leg is actually slowing the person down during the first 30% and is pushing the person forward during the last 70% of the gait cycle. The peak of the horizontal forward push occurs right before heel rise and toe off after which the swing phase is initiated.

While the kinetics and kinematics of the human gait are easily measureable, it also has a psychological side to it. Walking involves context awareness [9], or location awareness. Context awareness is a human's ability to automatically account for perturbations to the physical body while preparing and adjusting for such disturbances. The human body is a learning machine, which adapts to external perturbations with conscious and unconscious reaction and balancing forces. A good example of this gait context awareness is when someone is about to step onto a non-moving escalator. Their body automatically adjusts muscle tension and aligns its center of gravity anticipating escalator movement. Similarly, this can be observed by analyzing the preplanned trajectories when reaching for objects a known distance away [10, 11]. During walking if a repeated permutation is anticipated, an individual adapts their walking pattern in an unconscious and automatic manner to expend the least amount of energy expenditure.

Figure 6: Conventional Escalator. [41]

Abnormalities in the human gait are numerous and are a whole topic on their own. For the relevance to this manuscript I focus on the anatomy of the asymmetric walking pattern adapted by persons who have experienced central nervous system damage, such as stroke [31, 32], Parkinson disease [33] coma patients, or individuals that have suffered damage to the spinal cord, brainstem, cerebellum [31], and motor cortex. This division in abnormal gait I will refer to as asymmetric gait or hemiplegic gait. Little is known about the direct causes of gait asymmetries, however some studies in various animals [34, 35] suggest that abnormalities in rhythmic patterns such as walking stems in the auto-activity of localized networks of neurons or central pattern generators within an animal's nervous system. Also, studies in infants and adults [36, 37] lead to the conclusion that there are central pattern generators responsible for left-right leg pattern movement.

While the essential neurological causes of hemiplegic gait are still uncertain, the physical anatomy of a hemiplegic gait is clear and measurable. Using a wearable planer footprint analysis system, Gavira et al. [38] showed that hemiplegic patients spend less time and rely less on their lagging foot for support. It was also shown that the stride length was much shorter, walking velocity much lower, step duration longer, and reactive force values and temporal correspondences significantly different in the midfoot and forefoot.

2.2 : Gait Rehabilitation

A normal gait is very adaptive in nature and can be altered over a conscious short term feedback reaction type movement when sudden perturbations are introduced, such as an individual slightly tripping over a folded rug and recovering. Normal gait also has been shown to be altered in a more unconscious fashion with longer feed-forward learned type movements when continuous external physical stimuli is applied onto each limb while walking [3] or when walking with an uneven belt speed ratio on a split belt treadmill [2, 21]. The repetitive asymmetric stimulus on a symmetric gait over a longer period of time has been shown to have altering aftereffects.

Not only has it been shown that the adult human gait can be altered to automatically perform a learned movement, but studies in animals and infants [5] have shown similar results in ferrets [12], spinalized cats [13], rats [14], and frogs [15]. These studies also show that damage to the cerebella in animals hinders the ability for a feed-forward learned type of adaption in gait but do not affect the feedback reaction type alteration in walking gait [17] suggesting that the feed-forward gait adaptation is controlled by the cerebella.

Reisman et al. [2] showed this principle by setting up a split-belt treadmill as shown in Figure 7, where the track velocity ratio was forced to 2:1. Hemiplegic patients were conditioned with this asymmetric track velocity ratio for fifteen minutes during which the subjects gait adapted to a more symmetric gait. As the split-belt treadmill was switched back to a 1:1 track velocity ratio a symmetric gait after effect was observed. Although there was a positive rehabilitation effect using this split-belt treadmill gait conditioning method, the aftereffect was short lived lasting only for a couple of seconds.

Figure 7: Conventional Split-belt Treadmill. [39]

It is suggested that the long term aspects of this effect should be studied. These long term split belt treadmill effects are of course impossible to study with a split belt treadmill. A test subject can only be held on a split belt treadmill for a short period of time. Hence, a mobile device such as the gait enhancing mobile shoe (GEMS) can be utilized to observe such long term effects by letting test subjects wear the rehabilitation shoe over an extended period of time, where the severity of the after effects is periodically measured.

The method by which long-term effects would be trained is by letting the test subject wear the shoe on the weak leg and so limiting the forward motion of the weak leg. This motivates the individual to lengthen the forward distance where the initial heel contact point is. The GEMS also pushes the leg backwards simulating a correct gait. It is hypothesized that prolonged wearing of the GEMS will have positive after-effects helping asymmetric walking patients adapt a more normal walking gait over a longer period of wearing the GEMS. This application of the GEMS also has a potential to increase muscle impedance through the external perturbations [18], resulting in an altered walking gait.

Even if no long term permanent aftereffects are found to be present, the GEMS can still be used to correct asymmetric walking patterns by wearing the shoe on the strong leg and letting it swing past the stance phase, limiting forward progression, and letting individuals toe off with that leg. As a result both legs will push the individual forward by similar distances, evening out the asymmetric gait. This is important considering that post-stroke patients do not bring one leg back far enough, causing a limp. The result is the shortening of the stance phase, causing an unsuccessful toe off to efficiently propel them forward.

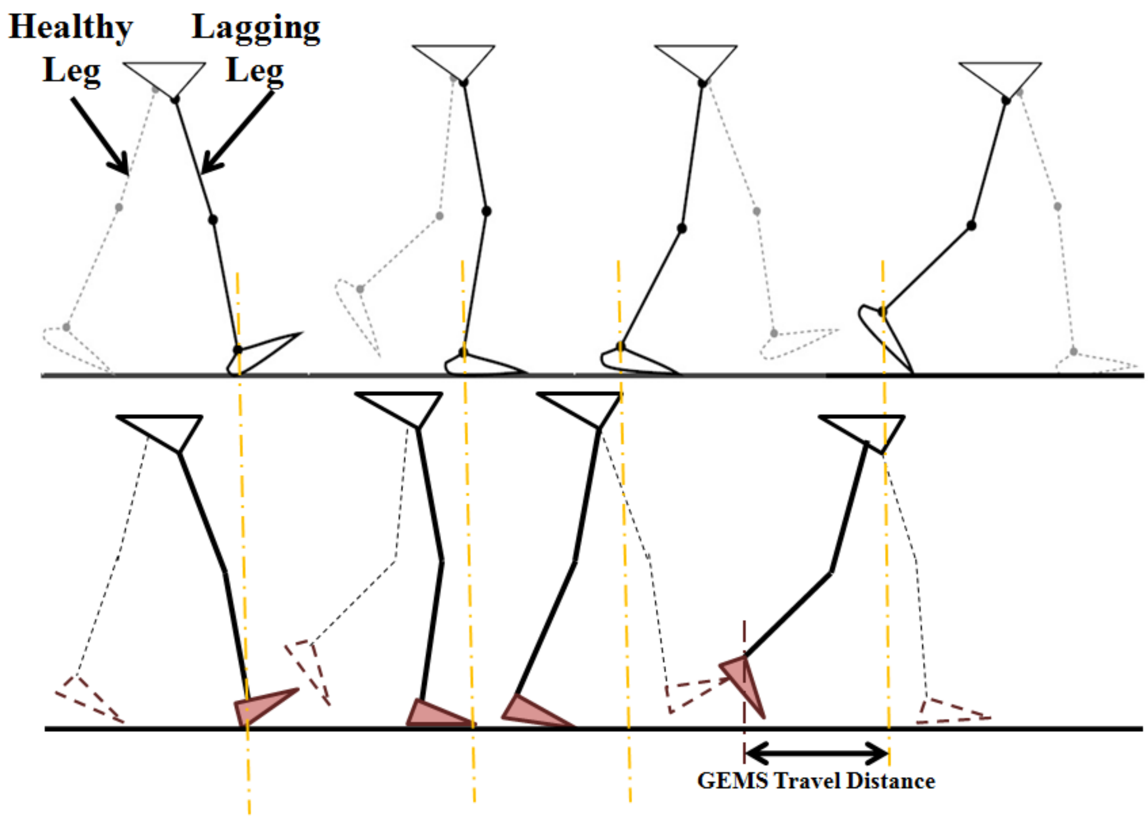

Figure 8: Rehabilitation method for asymmetric gait based on exaggeration where the GEMS is worn on lagging leg. Lagging leg is pushed backward motivating individual to perform a healthier toe off

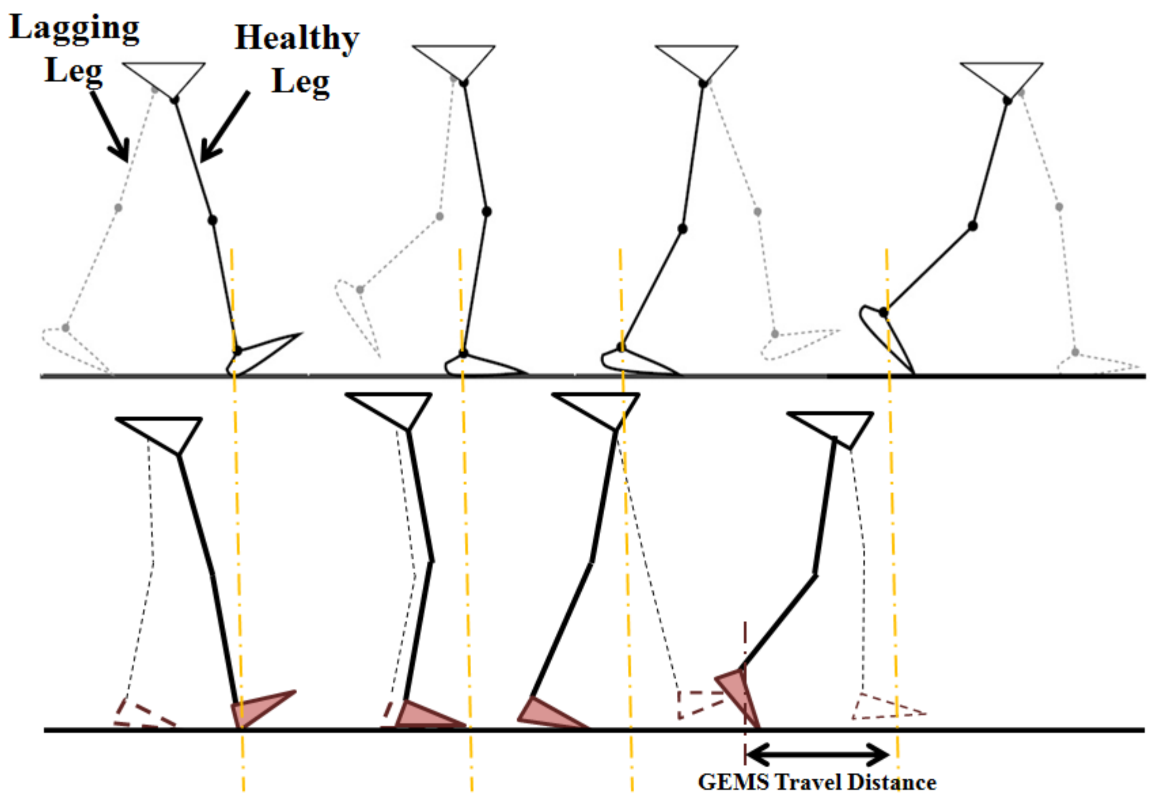

Figure 9: Rehabilitation method for asymmetric gait based on compensation where the GEMS is worn on healthy leg. This method evens out the forward progression between both the healthy and lagging leg, generating a symmetric gait

2.3 : GEMS and Context Awareness

As explained in section 2.3, context awareness is the human's ability to automatically account for perturbations to the physical body while preparing and adjusting for such disturbances [9]. The concept of a broken escalator effect was analyzed and it was proven that the body relies heavily on visual sensory and visual cues for balancing [40]. For example, it is much harder to balance one's own body on one foot with eyes closed compared to having one's eyes open. This leads me to believe that the body's visual exteroception plays a dominant role in the conditioning of a walking gait and in turn the adaptation of symmetric gait in hemiplegic patients.

It is this context awareness that is hypothesized to be an integrating factor in the inability to store the previously described feed forward motion learned in split belt gait manipulation research [2]. While after effects can be achieved [1, 2], as subjects adapt to the asymmetric treadmill speed and are sat out to walk over ground, the learned gait motion disappears within seconds. Although the kinematics of walking on a treadmill and the act of walking over ground seem identical, the visual cues and kinetics are different.

The concept of the GEMS eliminates this problem with context awareness during the gait adaptation process. With the GEMS the human gait is altered so that it is in line with the body's context awareness. The walking gait is slowly altered using the split-belt treadmill concept, however during conditioning there is no disconnect between the visual cues during the conditioning process and the visual cues after the adaptation process.

2.4 : Previous GEMS Model

An existing GEMS prototype [1], shown in Figure 10 has been developed which successfully generated the desired backward motion simulating a split-belt treadmill with a 2:1 track velocity ratio. However, large variations from step to step were observed, which is hypothesized to prevent the user from fully adapting to the motion.

Figure 10: Initial existing GEMS prototype. [1]

The existing prototype consists of a rear wheel at the user's heel, a middle roller, and a rubber piece to use for toe off. The rear wheel's axle is attached to the geared rack which when a downward force is applied the wheel will cause a backward motion. Figure 11 shows this geared rack in closer detail.

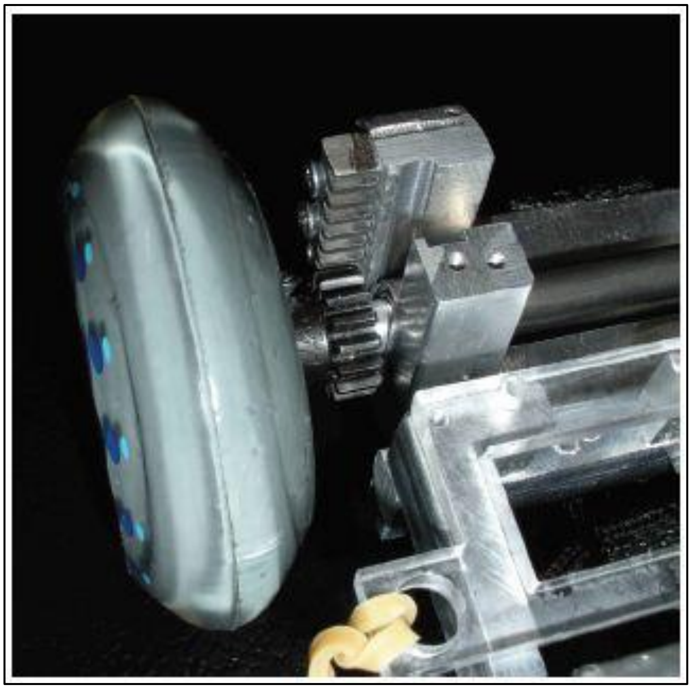

Figure 11: Rear mechanisms that cause backward motion when user's weight is applied. [1]

The middle roller is coupled with a rail moving forward as the shoe moves backwards, providing a constant two point contact between the shoe and the ground until toe off is initiated. Figure 12 shows the kinematics of the shoe as the stance phase is initiated until toe off is complete.

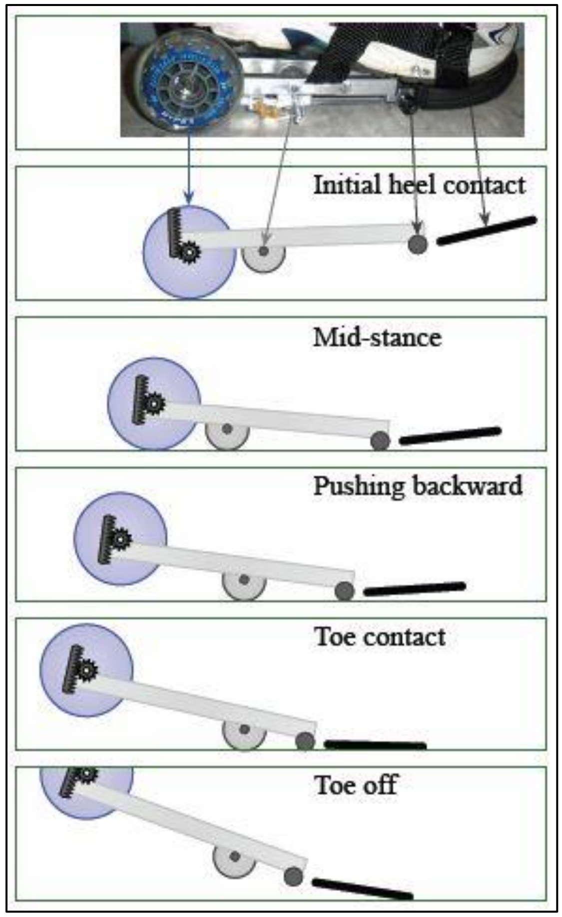

Figure 12: GEMS motion throughout the stance phase. [1]

The front surface of the existing shoe consists of a free roller and a rubber surface to increase friction during toe off. The rubber surface is just like any other shoe surface and is relatively flexible allowing the wearer to bend this surface when pushing oneself forward.

This version of the GEMS worked as intended and slid the user's foot backward by a total of 10 in (25 cm) on most steps. The GEMS initial prototype yielded similar results as the 2:1 ratio split belt treadmill, while wearing the shoe. However, only minor aftereffects were observed. Only very short term aftereffects of two steps were noted.

This unreliability is thought to be caused by the large variation in dynamics from step to step using the GEMS, where the user had to consciously go through the motions of walking compared to the reliable and even dynamics of a split belt treadmill generating a constant velocity profile. The second GEMS version eliminates this unpredictability by having the ability to regulate backward horizontal motion.

Although the previous design was able to move the wearer's foot backwards, it performed the motion in a jerky, uncontrolled, and unnatural manner. Also instead of pushing the wearer's foot backwards, it acted as if the wearer was slipping on ice or a slippery surface. It is assumed that this uncontrolled motion activates the bodies balancing and recovery reflexes, thus hindering a positive adaptation of an altered walking pattern. In addition, as a result of the previous model's large horizontal backward motion of 10 in (25cm), the walking speed was decreased. A huge limitation of the previous GEMS model was that it had little adjustability in backward motion velocity, travel distance, or travel direction. There was also a variation of backward stepping distance in each step observed to be caused in the variation of applied user force and walking speed. The next section will discuss how these limitations will be overcome in the controlled version of the second version of the GEMS. It proceeds to outline each design aspect of the new GEMS.

Chapter 3 : Design and Assembly

While the broad concept of this version of the GEMS stems from the previous version, the new version is a complete redesign utilizing different mechanical concepts. The improved GEMS design aims to smooth out the transitions between phases in a human gait by regulating the horizontal backward motion of the foot. This controlled motion makes the redesigned GEMS similar to the foot motion experienced when walking on a split belt treadmill. The new redesign still acts in a passive manner in that it utilizes the wearer's vertical downward motion to create horizontal backward motion.

This new version of the GEMS utilizes an Archimedean spiral shaped wheel to passively push the user's foot backwards with only the user's weight as energy input. Without restriction this backward motion is sudden and uncontrolled, hence the torque created by the GEMS wheels is reduced through a gear train so that a small magnetic particle brake can determine the magnitude of resistance to backward motion of the shoe. The magnetic particle brake is controlled by a microcontroller, which determines the magnitude and timing of resistance through a potentiometer coupled to the gear train and an accelerometer attached to the GEMS frame. While one of the user's feet is securely strapped to the GEMS, the opposite foot is strapped to a raised support platform which has the same dimensional and weight properties as the GEMS.

3.1 : Wheel Shape

A vital part of the GEMS design is its wheel shape. The wheels are designed based on the Archimedean spiral shape shown in Figure 13.

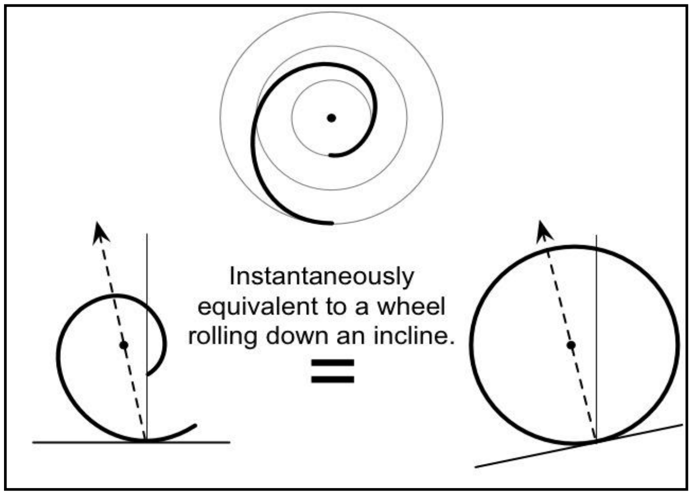

Figure 13: The GEMS wheel shape is designed so that when normal vertical force is applied it behaves as in rolling down a slope

The radius changes throughout the rotation angle, which is essentially akin to rolling down a hill with a uniform wheel, but in this case the slope is attached to the foot and is not part of the ground. The radius, *R*, over a whole rotation of an Archimedean spiral shape is obtained by Equation 1,

$$R(\theta) = b\theta^{\frac{1}{n}} \qquad (1)$$

where the constants *b* and *n* constitute the size and shape of the Archimedean spiral.

Because of the passive nature of the GEMS, in that it rolls on its own weight due to an asymmetric nature of the wheel, the Archimedean spiral is utilized in creating a passive GEMS to where the user applies their own weight to create the shoe's backward motion. In this shape the wearer applies a vertical force during the stance phase that can be directly related to the instantaneous horizontal backward reaction force through Equation 2.

$$F_H = F_V \left(\frac{L}{R}\right) \qquad (2)$$

Where L is the instantaneous perpendicular distance between the wheel center and the ground contact point and R is the distance between the ground and wheel center or axle attachment.

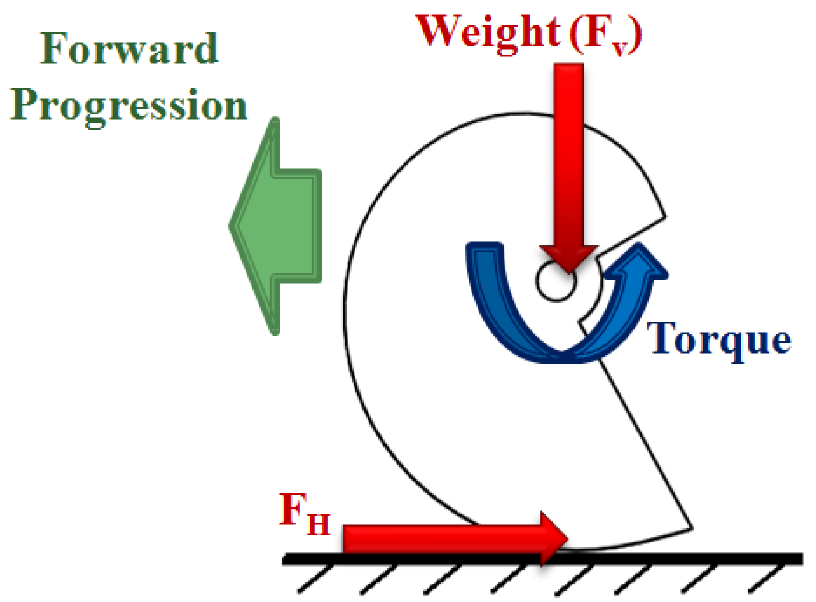

Figure 14: The GEMS wheel shape redirects vertical user weight force into a horizontal ground reaction applying a torque at the wheel axle creating forward progression

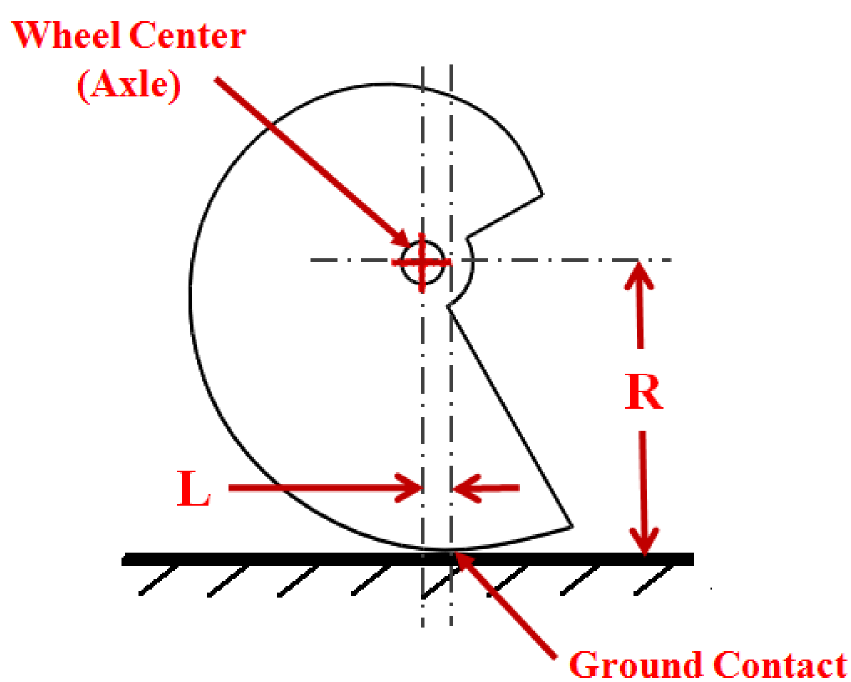

Figure 15: GEMS Wheels shape length, L, and radius, R, parameters

Using the Archimedean spiral wheel shape allows the manipulation of several customized variables such as the horizontal travel distance (270° wheel sector perimeter), horizontal maximum velocity, overall shoe height, and of course horizontal backward force exerted by the shoe onto the wearer's foot. Considering all wheel shape variables and by using a custom wheel shape optimization tool (Appendix C), a wheel shape of appropriate dimensions was selected. The resulting wheel parameters are shown in Table 1.

Table 1: Wheel shape parameters chosen for the new GEMS

Shortest Radius, R_1 (in):	0.75
Longest Radius, R_2 (in):	2.00
Shape Constant, n:	1.07
270° Wheel Sector Perimeter, P (in):	6.70
Average Horizontal Force at 800N, F_H (N):	270

The average horizontal force exerted by the wheel was found using Equation 3,

$$F_{H.AVG} = \frac{1}{R_2 - R_1} \int_{R_1}^{R_2} F_H(R)\, dr \qquad (3)$$

This design of the shoe also allows the direction of the wheels to be changed so the shoe can similarly provide a forward motion. This allows me to put one shoe on each foot where each foot generates an opposite horizontal motion. Using two shoes would provide the rehabilitative split-motion effects in an environment that most closely resembles walking over ground and would allow the greatest ground motion differential while providing the same forward progression as walking without the shoes does. However, this thesis work only considers the design, construction, and testing of one single shoe pushing the wearer's foot backwards during the stance phase.

As shown in Figure 5 in section 2.1, a maximum 170N (38lb) horizontal force is applied slightly after the person makes heel contact in the backward direction and slightly before a person initiates toe off in the forward direction (assisting). The average backward force of 270N (36lb) exerted by the wheel shape in the horizontal direction easily overcomes the initial horizontal force exerted by a person's foot after heel contact. Overcompensating for the wheel's backward force is intended to prevent the user from slipping forward after heel contact.

Also the design goal of 6.5in (16.5cm) wheel travel distance is accomplished by the selected wheel shape which has a perimeter of 6.7in (17in). This slight overcompensation is appropriate considering that the wheel does not always ideally touch down at the perimeter beginning.

The assembly method to mate the wheel to a 0.25in (0.635cm) diameter steel axle is simply the axle pulled through the wheel center with two set screws 60° apart with one set screw laying on a flat that is machined onto the end of the axle. The side view of this assembly method is shown in Figure 16.

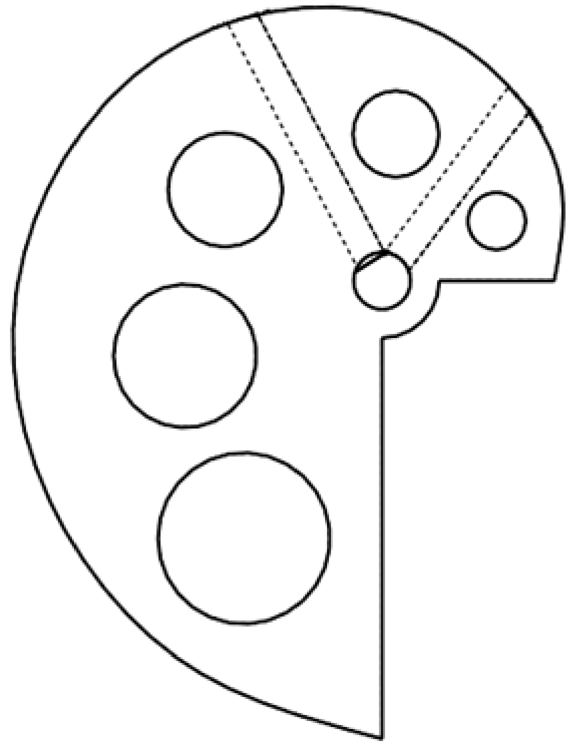

Figure 16: Side view of actual GEMS wheel mated to axle

Considering the selected wheel shape, as an 800N (180lb) individual steps on all four wheel in the middle of the stance phase, an average torque of 80.1lb-in (9.0N-m) is exerted on all four wheels, equating an average of 20.0lb-in (2.3N-m) at each individual wheel. Bearing that and my goal to reduce shoe weight, the wheels were made out of aluminum. Also, to further reduce wheel weight holes were drilled through the wheel. The option of selecting aluminum for axle material was taken into account, however, reaction forces exerted from the miter gear set in the drive train were too large and caused the aluminum axle to bend, hence a steel 0.25in (0.635cm) axle was selected. Dimensions and positioning of all four wheels are shown in appendix E.

The front and back axle of the GEMS are coupled with a set of sprockets and a chain between the two steel sprockets. These sprockets are pinned to each steel axle. The specifications and dimensioning of these individual components can be shown in appendix D while the global setup of the chain and sprocket axle coupling can be viewed in appendix E. The coupling of the front and back axle through a rubber timing belt with an intermediate custom made belt failed because the torque on the wheel was too large, causing the belt to slip.

3.2 : Gear Train and Magnetic Particle Brake

My new design alleviates the largest deficiency of the previous shoe: the large motion variability generated and the jerkiness during each step. To overcome this limitation, the angular velocity of the wheels and in turn the movement of the GEMS in the new design can be controlled by a braking system. This braking system consists of a gear train and a 0-24V small magnetic particle brake, which when combined is strong enough to resist any shoe motion as a person is stepping on the shoe. A magnetic particle brake is essentially a voltage actuated clutch; the more voltage is applied, the harder two internal plates push together impeding shaft rotation. An electric motor capable of generating the same necessary movements would require too much power and would not be available within the weight restriction.

The front axle is mated to the rear axle with a chain and sprockets. As the wearer applies a vertical downward force onto any or all of the four wheels, the combined torque distributed from the rear axle through the gear train and to the magnetic particle brake for resistance.

The maximum torque exerted by the wheels can be estimated using Equation 1 combined with Equation 4,

$$T = F_{H.AVG} R_2 \qquad (4)$$

Two sets of Miter gears were used to redirect the gear train for a space efficient fit. Three spur gears with three 4:1 (60 T–15 T) gear reductions each were used to reduce the torque applied by the GEMS wheels by a factor of 64. This gear train design reduces the input torque at a wheel axle from 40lb-in (4.5 N-m) to 0.625lb-in (0.071 N-m).

A 1 lb-in magnetic particle brake was selected to apply resistance to the reduced torque of to 0.625lb-in (0.071 N-m). The gear train and magnetic particle brake setup is schematically shown in Figure 17. Friction forces and forces from the spring actuated wheel reset mechanism were also taken into account during magnetic particle brake selection.

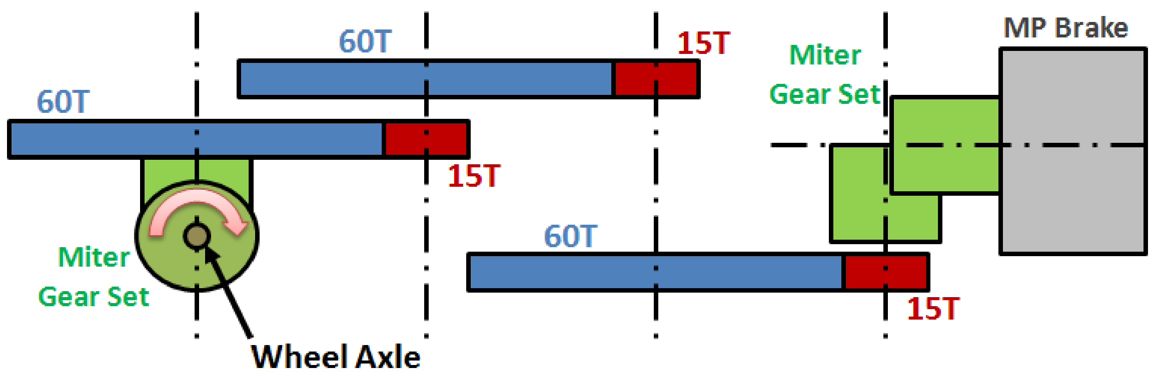

Figure 17: Side view of the gear train of the GEMS including magnetic particle brake

Note that I chose to use a brake to resist the natural shoe movement generated by the users weight applied to the wheels of the GEMS, a spring then generates the return force to the whole mechanism.

3.2.1 Magnetic Particle Brake

The GEMS is a mechanically passive device that utilizes the wearer's weight for movement in the horizontal direction. This redirected force yields horizontal GEMS movement by wheel rotation, this rotation is controlled through a gear train coupled to a magnetic particle brake. Figure 18 shows the magnetic particle brake chosen to resist and stop the GEMS horizontal movement.

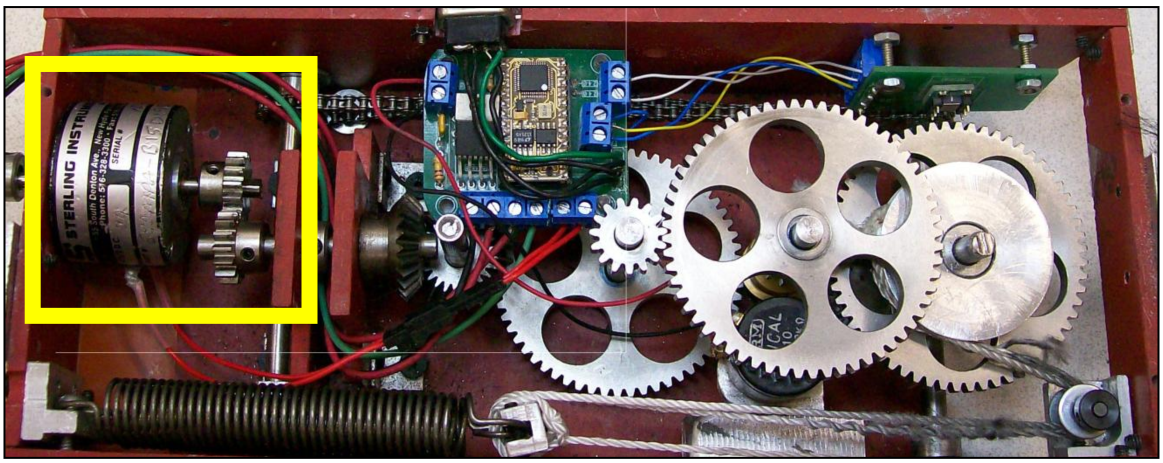

Figure 18: 1lb-in magnetic particle brake utilized in the GEMS design

The specification and option catalog page for the magnetic particle brake is shown in appendix D. A magnetic particle brake is essentially a miniature clutch consisting of two parallel plates pressed against each other creating desired friction, which in turn impedes shaft rotation.

Considering the options outlined in the vendor's catalog and the fact that the brake needs to stop 0.625lb-in (0.071N-m) of torque coming from the wheel axle through the gear train, the 1lb-in magnetic particle brake was selected. Although the later discussed reset mechanism and frictional forces impede wheel rotation, a dynamic force of a stepping motion is considered, yielding a higher torque needing to be stopped. Also the selected brake weighs 1lb (0.45kg), which is a reasonable weight considering the weight criteria for the GEMS is 2.2lb (1 kg).

An electric motor was considered to handle the same type of GEMS movement but no electric motor was found small and light enough to control the torque exerted by the GEMS wheels, hence a passive magnetic particle brake was used.

The magnetic particle brake is powered by a non-inverting op-amp circuit shown in Figure 19.

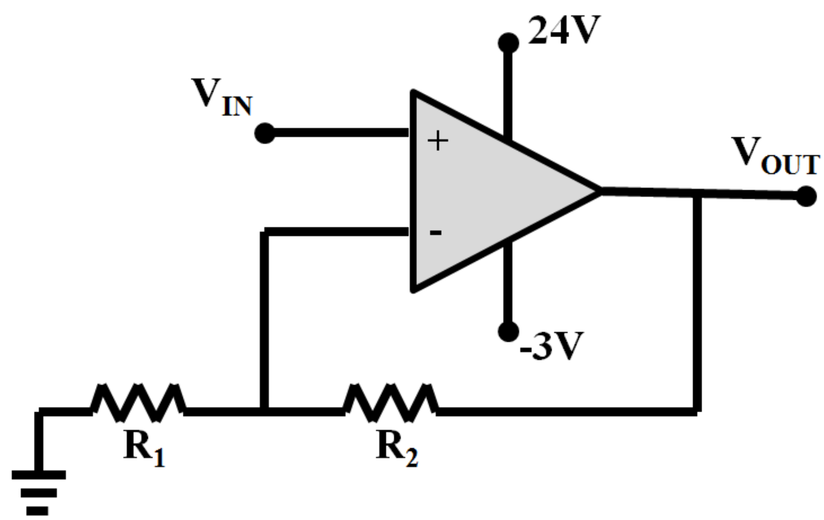

Figure 19: Non-Inverting op-amp circuit used to output 0-24 to the magnetic particle brake

Shown in the above Figure is the circuit that amplifies the a 0-5V pulse width modulation (PWM) signal from the microcontroller and outputs a proportional 0-24V signal to the magnetic particle brake, where 0V is no brake resistance and 24V is the full 1lb-in (0.11N-m) of resistance. The whole electrical circuit including the circuit outlined above can be viewed in Appendix A.

3.2.2 Gear Train

The gear train is used to reduce the torque from the wheels to a torque that can be handled by a small magnetic particle brake. The magnetic particle brake selected for implementing impedance on the movements of the GEMS can exert a maximum torque of 1lb-in. The gear train reduces the wheel torque from 40lb-in (4.5N-m) to a torque that can be stopped by the magnetic particle brake.

The gear train is made up of three 4:1 gear reductions for a final 64:1 total reduction in torque. Given the 40lb-in (4.5N-m) input torque on heel contact, the magnetic particle brake receives 0.625lb-in (0.071N-m). The slight over-compensation of gear reduction stems solely from the larger dynamic gait forces and magnetic particle brake availability options. While irrelevant to the brake selection, it is worth mentioning that at a maximum wheel angular velocity of 10rpm, the angular velocity at the magnetic particle brake is 640rpm, which is well within the brake's operating speed.

The gear train includes two ninety degree Miter gear sets that allow the 60 tooth and 15 tooth spur gears to be rotated in such a way that their flat parts are parallel to the ground. This setup of spur gears gives the most efficient fit inside the GEMS giving the GEMS an optimal height for the components utilized.

These three reductions are done with three sets of 60T–15T reductions rotated by two sets of Miter gears. This setup is schematically depicted in Figure 17 and the dimensional details are shown in appendix E. Actual images of the gear train setup is shown in Figure 20. Considering the large torque that is exerted by the wheel axle and transferred through the gear train, the Miter gear sets and the spur gears are chosen to be plain carbon steel. During the initial material selection process, plastic Miter gears were used which failed due to large reaction forces. Although much lighter, another problem with plastic gear sets is that they are very hard to mate to metal rotation shafts and wheel axles due to the low yield strength of the plastic.

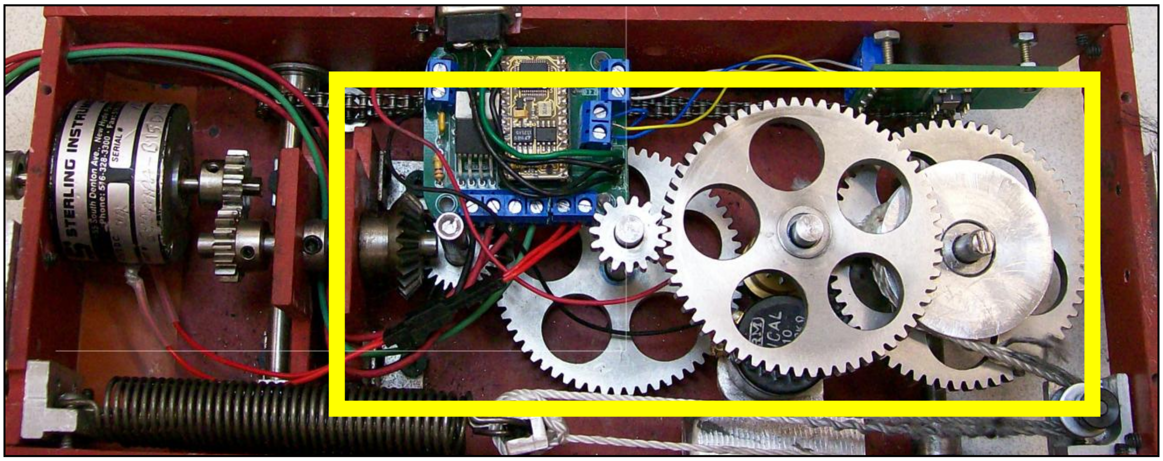

Figure 20: GEMS gear train

Since the GEMS wheels create a large torque, the first Miter gear set is exposed to large reaction forces pushing the Miter gear set apart. These reaction forces push the top Miter gear into the top frame cover and the bottom Miter gear to the side. These large reaction forces require a stiff bracket in order to keep the Miter gear set meshed during the GEMS operation. This bracket was custom made with aluminum and bolted to the bottom of the shoe frame (Figure 21). Also, to keep the Miter gear meshed an aluminum plate was mounted on top of the GEMS frame cover so that the Miter gear reaction forces do not push the rotation shaft upwards, this mounted aluminum plate is shown in Figure 22. Specifications and dimensions of the Miter gear set are shown in appendix D.

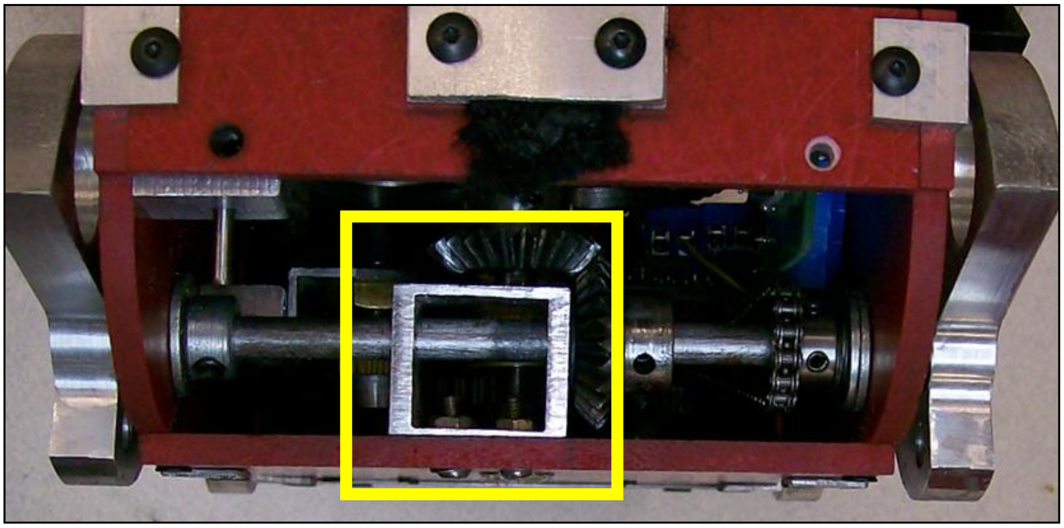

Figure 21: Front miter gear aluminum bracket

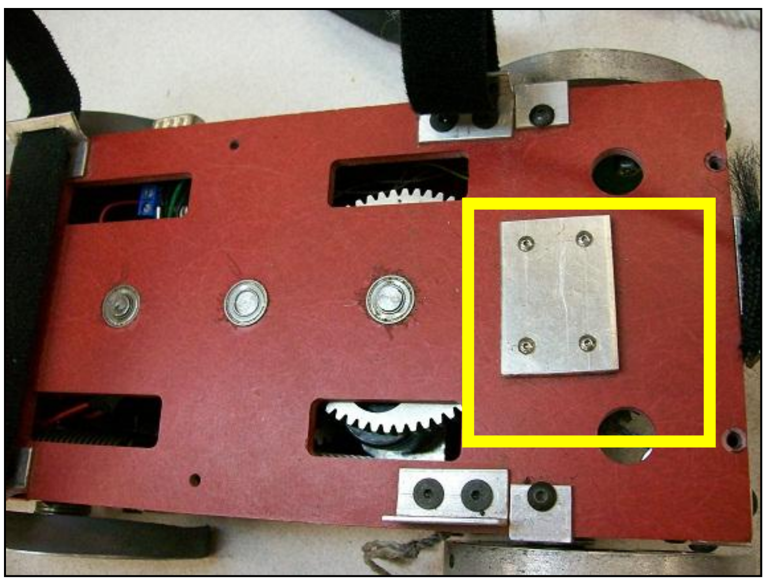

Figure 22: Aluminum plate on top of the GEMS frame cover preventing unmashing of miter gear set

The vertical rotation shafts of the spur gears are also made of steel and are held into place by appropriate roller bearings. The gears are pinned with a 0.125in (0.318cm) steel pins to the 0.25in (0.635cm) wheel axles and rotation shafts.

3.3 : Wheel Reset Mechanism

In order for the shoe dynamics to be identical every step, the GEMS resets the wheel position using the spring mechanism schematically shown in Figure 23. This reset mechanism consists of two extension springs, nylon strings, a small redirect pulley, and a pulley which is attached to the first gear axle.

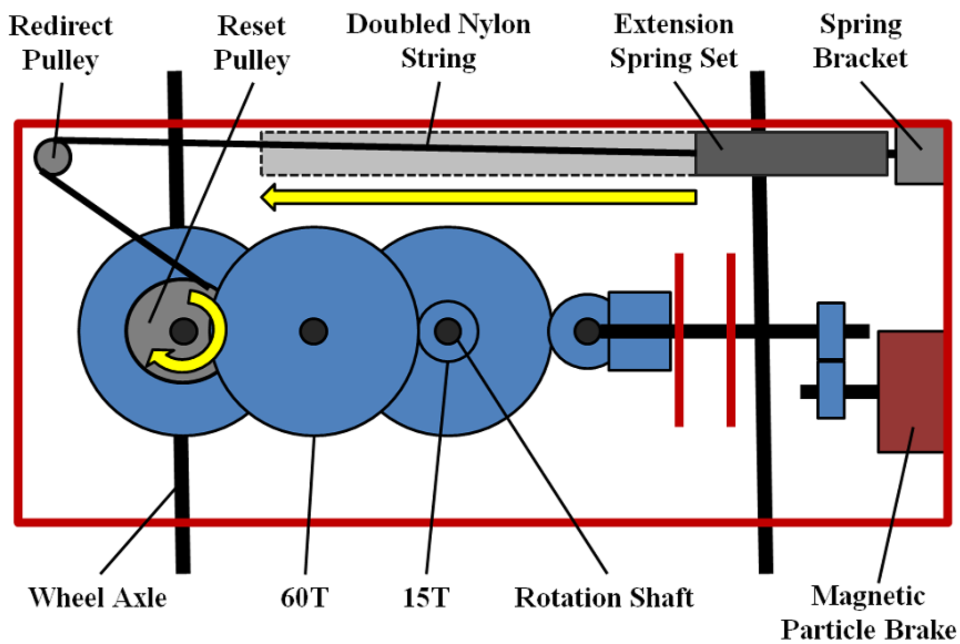

Figure 23: Top view of the GEMS showing the wheel reset mechanism. As the first rotation shaft rotates clockwise the extension spring set extends

As the wearer applies a vertical downward force on the wheels during the stance phase, the rotation of the wheels also causes the pulley to rotate, pulling the two extension springs apart. This potential energy stored in the extension springs is released during the swing phase so the wheels are rotated back to their initial position and ready for a subsequent step. The springs were selected so that their force can overcome all internal friction of the system while having a sufficient stretch length and stiffness.

A pulley is mated to the first rotation shaft of the gear train, on top of the first 60T gear as shown in Figure 23. A doubled nylon string is attached to this mated pulley, pulled across a small redirect pulley, and attached to a set of extension springs, which in turn are attached to the GEMS frame by a custom aluminum spring bracket. As the GEMS wheels rotates, so does the Miter gear attached to the axle and in turn the first vertical rotation shaft of the gear train with the mated metal pulley. The nylon string that is attached to this pulley is directed across a smaller redirect pulley which then pulls a set of extension springs apart. Once the GEMS is lifted off the ground during the swing phase in the gait cycle and the magnetic particle brake is released, the extension springs and so the GEMS wheels quickly return to its initial position.

Selecting the extension spring which can overcome this torque is an iterative process that accounts for several factors: Free length, maximum extension spring selection, stiffness, force at extension lengths, availability, and the consideration of combinations of springs in parallel and in series.

Combined internal static and dynamic frictional forces are hard to predict and so to correctly account for all the spring force required to rotate the whole mechanism back to its initial position against all frictional and damping forces, a simple setup was used as depicted in Figure 24.

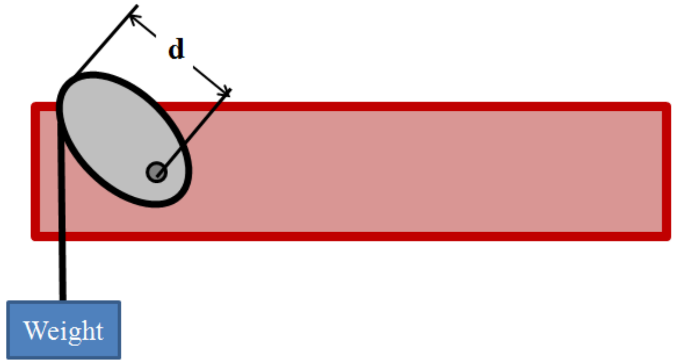

Figure 24: To estimate the spring force need to reset the GEMS, a simple setup was used.

A string was tied around the circumference of a wheel of the GEMS and weights were added to the string end until the whole mechanism started rotating. Knowing the wheel radius and the weight, a torque of 10.5lb-in (1.2N-m) on the wheel axle was calculated. This torque is required to overcome all internal static friction and damping of the GEMS and rotate the wheel to its initial position.

The positioning and stiffness of the spring is also a function of where the reset pulley is placed in the gear train and what the radius of the reset pulley is. The further down the pulley is placed in the gear train, the less torque is needed to reset the shoe. Placing a reset pulley on the first rotational shaft of the gear train would require 10.5lb-in (1.2 N/m), while the torque required to reset the shoe by placing the reset pulley on the second rotation shaft is 2.625lb-in (0.30 N/m). Also of course, reducing the radius of the reset pulley yields a larger force required to overcome the torque needed to reset the whole shoe to its initial position. So the position and size of the reset pulley dictates the extension length of the spring, in that as the reset pulley moves further down the gear train, more rotations are required to reset the wheels and the greater the circumference the reset pulley is, the longer distance the spring is eventually extended.

Given these constraints and spring availability, extension springs were placed in parallel with the reset pulley placed on the first rotation shaft of the gear train, again as shown in the schematic above in Figure 23.

In order to keep a pretension on the extension spring set before they are pulled apart, the extension springs are held slightly extended with another nylon spring attached to the frame of the GEMS as shown in Figure 25.

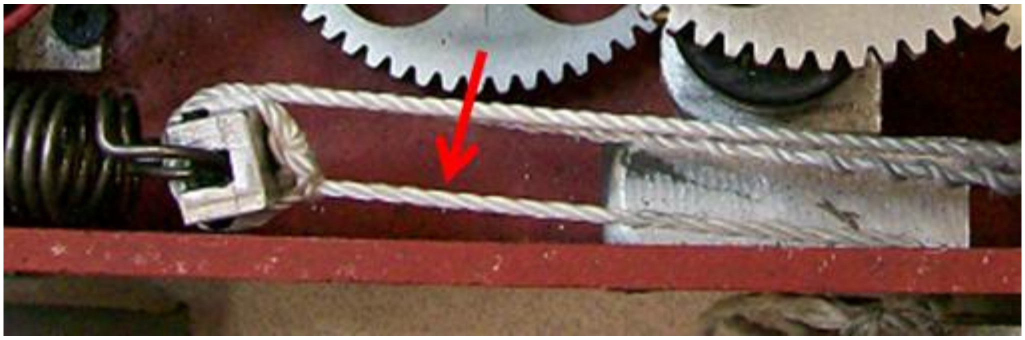

Figure 25: The extension springs are pre-tensioned by a nylon string attached to the frame

All the components of the wheel reset mechanism play off each other in that as one component changes, it affects the other components. The two parallel springs were selected with a sufficient stretch, a pre-tension, and a maximum force and max stretch length so that when incorporated with a sufficiently large reset pulley would adequately cover the needed 10.5lb-in (1.2N-m) torque to completely reset the shoe. Table 2 shows the spring properties of the chosen extension spring.

Table 2: Extension spring properties

Stiffness (bl/in)	2.5
Free Length (in)	3.5
Streched Length (in)	9.5
Outside Diameter (in)	0.5

To accommodate these springs, a custom made aluminum pulley of 1.0in (2.54cm) radius was selected and placed on top of the first 60T gear pinned to the first rotational shaft. This aluminum pulley was held into place by two set screws 180 degrees apart, screwed down onto the top of the 60T gear. On one side a second set screw was used as an attachment point for the doubled nylon string (Figure 26). For detailed reset pulley dimension refer to appendix E.

Figure 26: Aluminum reset pulley, redirect pulley, and doubled nylon string

A little redirect pulley of 0.225in (.573cm) radius was designed and custom machined out of aluminum with a steel pin holding this pulley, this pulley was placed in the back upper corner of the GEMS frame.

A nylon string was used to pull the extension springs apart. While wires and ropes were either inflexible or too thick, the nylon string was very low friction, strong, and very flexible, however by itself was too weak to withstand the extension spring set force when extended to the maximum, hence, the nylon string was doubled, cutting the tension in each chord by half.

The nylon string was then in turn attached to the extension springs using a specially made aluminum bracket machined in a way to where the both the extension springs neatly hooked on it and the nylon string tied around it.

The bracket that connects the GEMS frame to the extension spring is again machined out of a small block of aluminum and screwed into the back and the side of the GEMS.

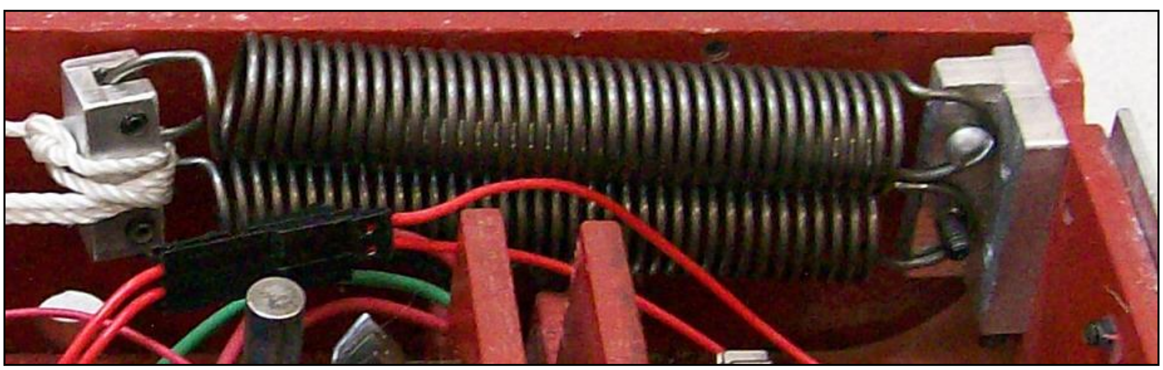

Figure 27: Spring to nylon string bracket (left) and spring to frame bracket (right)

A constant force spring was considered early in the GEMS design because of its attractive ability to exert constant force onto the system, this idea however was proven complicated to implement, and reduced the reliability of the GEMS shoe. The constant force spring needed a delicate guide and attachments in order for the spring not to coil up violently.

All dimensions and drawing concerning the wheel reset mechanism can be viewed in appendix E.

3.4 : Electronics

The GEMS varies the motion resistance through the magnetic particle brake using an op-amp circuit in conjunction with a BS2p24 microprocessor (Figure 28). Depending on what point in the gait cycle the wearer is, variable resistance is applied to the GEMS. Instances in the gait cycle are identified by using a rotational potentiometer and an accelerometer. While the potentiometer recognizes the wheel rotation, the accelerometer recognizes when heel contact and toe off occur. Heel contact is measured by the jerk applied to the wheel and frame of the GEMS, and toe off is determined when the shoe has tipped forward by 30 degrees. In order to easily reprogram the on-board microprocessor, an external RS232 connection was mounted outside the side of the GEMS. All electronics are powered by a small battery pack, which the user wears on their hip. The electrical diagram for the combined GEMS electronics is shown in appendix A.

3.4.1 Microcontroller

A Parallax BS2p24 microcontroller was used to collect sensory information from a potentiometer and an accelerometer, and control the timing and resistance of a magnetic particle brake and so in turn the GEMS movement. The specification and electrical diagram for the selected microcontroller are found in appendix D.

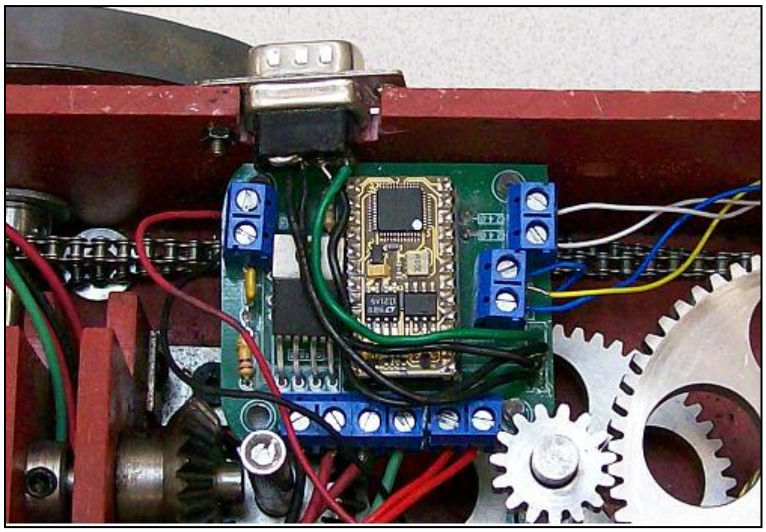

Figure 28: Parallax BS2p24 microcontroller integrated into the GEMS

This chosen microcontroller speed is 20 MHz which guarantees that acceleration instances are well captured while it while analyzing the potentiometer input and outputting appropriate resistive torque through the magnetic particle brake.

Programming the microcontroller was achieved by a RS232 cable that connected a desktop computer to the microcontroller. To minimize hassle the female connection of the RS232 connection coming from the microcontroller was pulled through the side of the GEMS (Figure 28).

The programming of the microcontroller for the GEMS was very straight forward and needed to be simple to enhance runtime speed. It included the following:

- Scanning of the potentiometer for wheel rotational position
- Scanning of accelerometer for shoe angle and sudden acceleration spike
- Determining where in the gait cycle the GEMS is located
- Dictating magnitude and timing of the resistance exerted by the magnetic particle brake
- Outputting of voltage dictating how much resistance the magnetic particle brake exerts

Initially proportional and derivative controls were to be programmed into the microcontroller but the result was unreliable and further investigation in code depended controls is needed. The final code assigned a set resistance to the magnetic particle brake at key instances of the gait. This code can be viewed in appendix F.

The BS2p24 was integrated into a distinctive circuit board drawn up in PCB Artist and printed by 4PCB.com company. This small circuit board schematic as it was printed is shown in Figure 29.

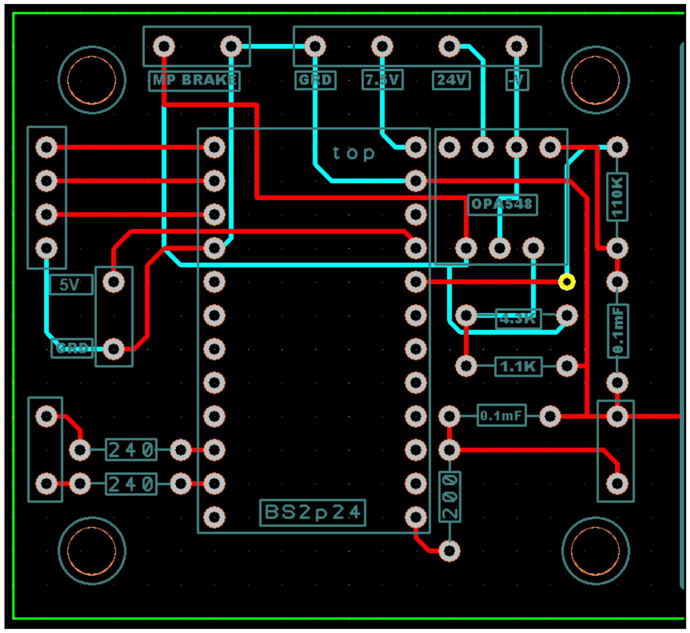

Figure 29: Circuit board for GEMS

The circuit board is mounted on a custom acrylic bracket which is screwed to the side of the GEMS right above the chain which connects the two axles. This acrylic bracket was produced by a VLS4.60 Universal Laser Systems laser cutter using 0.125in (0.32cm) clear acrylic.

3.4.2 Accelerometer

During the gait cycle there are some distinct instances that are important to the GEMS: Heel contact and Toe off. Both of these instances are borders for the stance phase and the swing phase and can be identified using a accelerometer. Heel contact and so the initiation of the stance phase is recognized both, by a sudden acceleration or jerk when the GEMS wheel hits the ground, and a slight tilt in the GEMS shoe as the foot is approaching heel contact. Toe off and so the initiation of the swing phase was recognized by a slight forward tilt of the foot. In these instances the accelerometer readings are recognized by the microcontroller and appropriate resistances are applied by the magnetic particle brake.

The Parallax Memsic 2125 Dual-Axis accelerometer (appendix D) was chosen to accomplish this task. In convenience this accelerometer is very easily complimented to the BS2p24 microcontroller due to the fact that it was produced for this type of microcontroller which reads a pulse width modulation (PWM) 0.5V input. Its power requirement is 3.3VDC to 5.0VDC, and is obtained by tapping into the BS2p24, which regulates it’s supply voltage of 5-12VDC down to 5VDC.

Due to tight space inside the GEMS the accelerometer was positioned in the top corner of the GEMS frame, right below the user’s heel. This convenient placement also allows observation of the acceleration change during heel contact. The positioning of the accelerometer is shown in Figure 30.

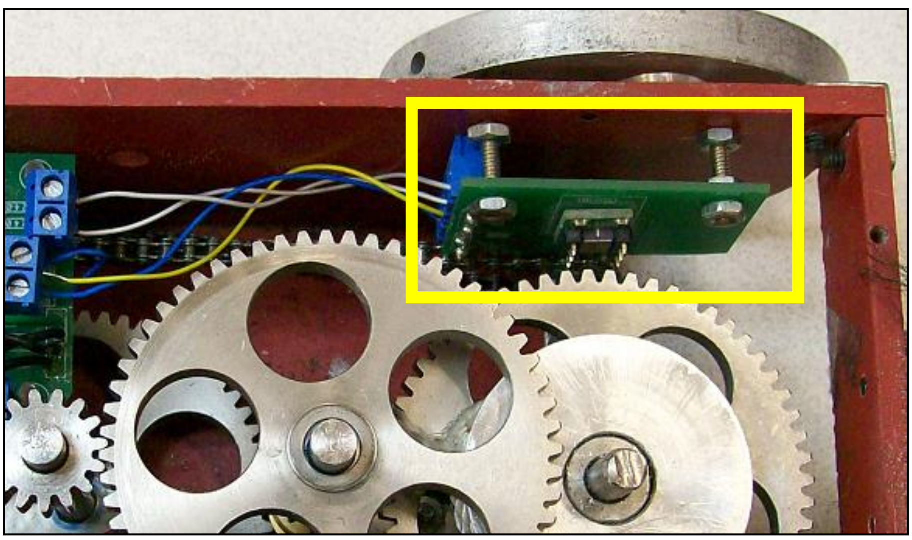

Figure 30: Position of accelerometer inside the GEMS

Also the schematic for the accelerometer as it relates to the microcontroller is shown in appendix A. The circuit board used on which the accelerometer lies was printed by using PCB Artist provided by 4PCB.com and is depicted in Figure 31.

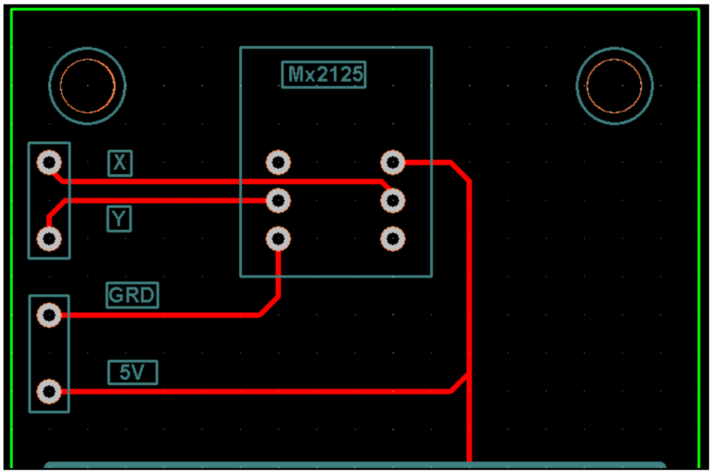

Figure 31: Circuit board for the accelerometer

3.4.3 Potentiometer

The rotational position of the GEMS wheels are also important to differentiate between the swing phase, when the magnetic particle brake applies no resistance, and the stance phase, when the magnetic particle brake applies a constant resistance impeding sudden GEMS motion. The potentiometer is attached to an aluminum bracket on the side of the GEMS next to the second rotation shaft of the gear train and right underneath the second 60T spur gear. The setup of the potentiometer is shown in Figure 32.

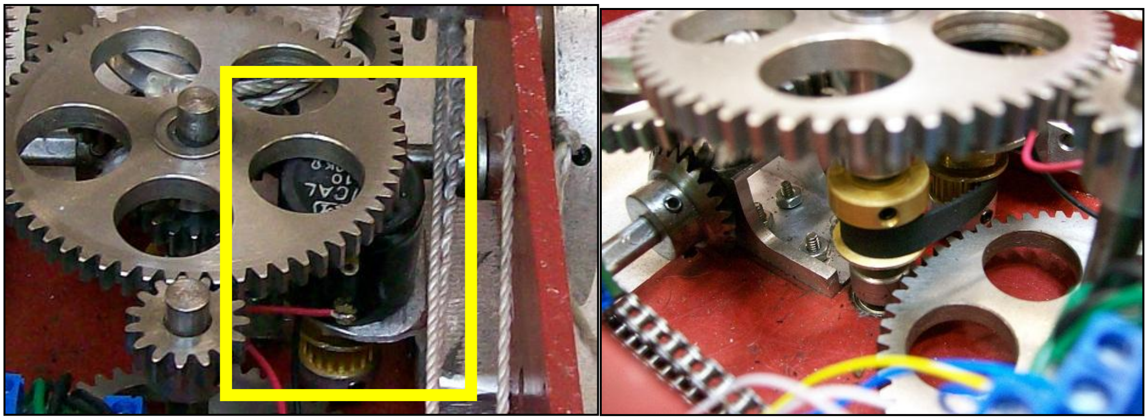

Figure 32: Potentiometer attached to the gear train shaft

A small aluminum timing belt pulley is attached to the potentiometer and an identical timing belt pulley is attached to the second rotation shaft of the gear train. In order to eliminate slippage and obtain an accurate reading, a small timing belt connects the two aluminum timing belt pulleys.

Due to the lack of space within the GEMS shoe the potentiometer had to be positioned away from moving parts of the shoe such as the extension springs used for the wheel reset mechanism (Section 3.3, Section 4.5). A custom machined bracket holds the potentiometer away from the GEMS wall so that when the extension spring is extended it does not interfere with the potentiometer. This aluminum bracket is screwed together by a set of screws to the GEMS wall.

Specification for the potentiometer component are found in appendix A, electrical diagram relating the potentiometer to the microcontroller is found in appendix A, and a GEMS layout which includes the potentiometer is found in appendix E.

3.4.4 Battery Pack

Electrical components in the GEMS require different voltages. The magnetic particle brake operates at 0-24VDC and the microcontroller operates at 5-12VDC (The accelerometer can tap into a regulated 5VDC pin on the microcontroller), and the op-amp also requires a -3VDC supply.

The electrical requirements for the magnetic particle brake, microcontroller, and accelerometer are shown in Table 3.

Table 3: Power requirement for GEMS components

	Voltage	**Current (Amp)**	**Resistance (Ohm)**	**Power (Watts)**
MP Brake	24.0	0.0850	290	2.000
Microcontroller	7.5	0.0400	125	0.020
Accelerometer	5.0	0.0005	*(neg)*	0.003
Op-Amp	*N/A*	0.0018	*(neg)*	*(neg)*

Considering the previously listed GEMS criteria of an uninterrupted operation criteria of 1.5 hours and the given electrical requirements outlined in Table 3, a battery pack battery pack consisting of three separate power supplies was custom made and is shown in Figure 33.

Figure 33: GEMS battery pack

A 7.5VDC power supply was simply made from five separate 1.5VDC AA batteries connected by AA battery holder. The same AA battery holder was tweaked to hold a separate two 1.5VDC AA batteries to create a -3VDC voltage. While the 24VDC supply running to the op-amp was made with two 12VDC 500mAH rechargeable Ni-Cd batteries connected together in parallel to yield 24VDC. Knowing the power requirements for each component, the 24VDC battery can be continuously be operational for 5.5 hours, 7.5VDC for 46 hours, and -3VDC for 50 hour, hence the time the GEMS is fully operational is 5.5 hours, which is well over the set criteria.

3.5 : GEMS Frame

The symmetric frame for the GEMS was chosen in a way so it could be used in both directions as the wheels can be repositioned. While the GEMS frame itself is important to the general operation of the GEMS, it was designed around other design requirements, which included the size of the gear train, the size and shape of the wheels, and the size of the magnetic particle brake. The simplest shape was chosen for the frame design, a rectangular box with rounded rubber pieces at the lower front and back corners. These rubber pieces support a stable heel contact and toe off during a gait cycle. It is made out of light and strong 0.1875in (0.5cm) fiberglass and held together with various aluminum brackets. Two rubber pieces were added to the lower front and back corner of the shoe so the wearer could effectively create a solid heel contact and toe off.

Fiberglass with 0.1875in (0.5cm) thickness was selected for the frame material. A Pugh analysis for the selection of this material can be reviewed in appendix B. This selection was based on fiberglass' strength and weight aspect as well as the material's machinabilty. The tensile strength for the fiberglass used for the GEMS frame is 30ksi (206MPa) lengthwise and 7ksi (48MPa) crosswise. It has an impact strength of 25 ft-lbs/in lengthwise and 4 ft-lbs/in crosswise. The thick rubber pieces that replaced lower front and back corners were also chosen to be of 0.1875in (0.4762cm) thickness.

The whole frame is held together with 0.0625in (0.1587cm) aluminum L-brackets at the corners of the frame. The L-brackets are held into place by screwing them into the frame.

Bearings holding wheel axles and rotation shafts for the drive axles were press fit into the frame at appropriate positions. These bearings accommodate a 0.25in (0.635cm) shaft for the wheel axle and for rotation shafts in the gear train.

All dimensions and specifications of the frame and its components can be reviewed in appendix E.

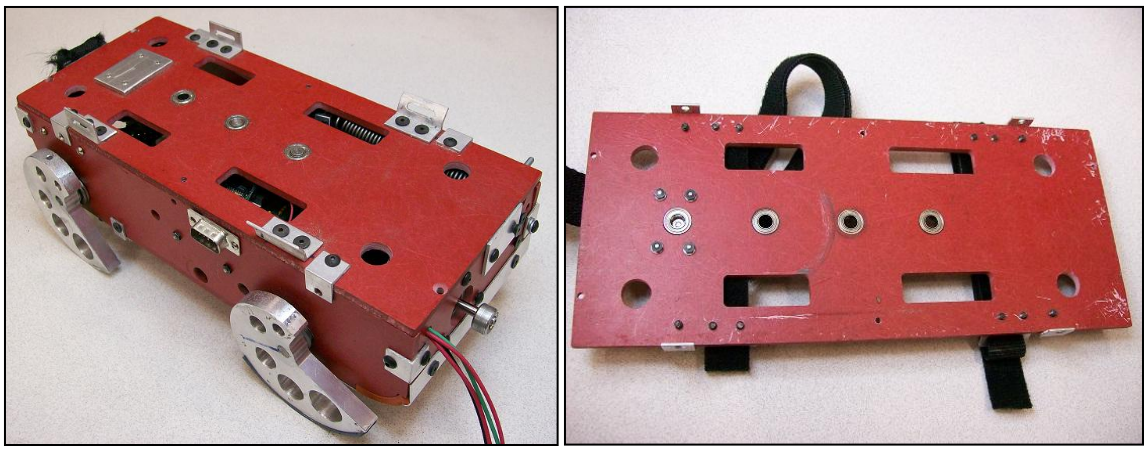

Figure 34: GEMS Frame and bottom of frame Cover

3.6 : Shoe Straps

During usage, the wearer's shoe is strapped down to the top of the GEMS. Identical to the first GEMS design, these straps were designed after a traditional sandal design (Figure 35), rigidly supporting the whole foot with minimal straps, this ensured minimal movement of the foot relative to the GEMS. Velcro straps were utilized for quick strapping and unstrapping of the wearer's shoe to the GEMS.

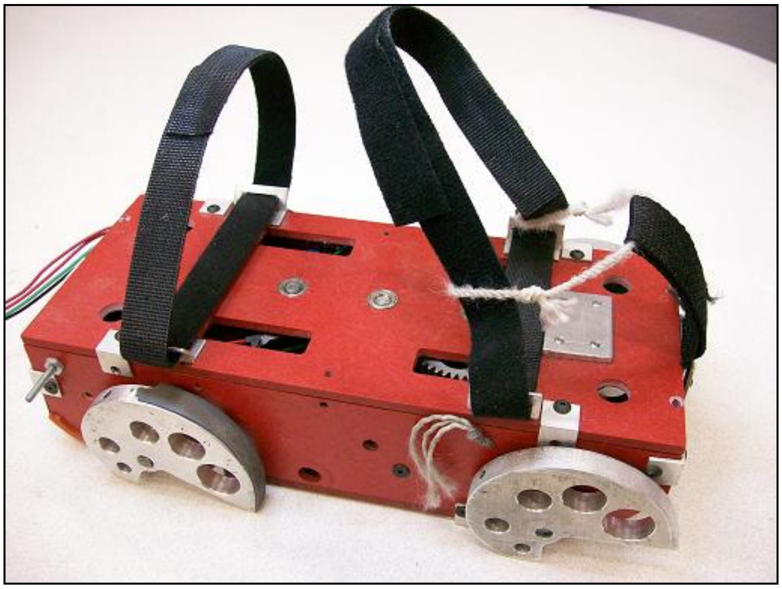

Figure 35: The GEMS straps are designed after traditional sandals

3.7 : Opposite Leg Support Platform

Because the GEMS is 2” (5cm) off the ground, a supporting platform of equal height and weight for the opposite foot was constructed. The support platform was designed to be the exact same dimensions, weight, and fastening style to eliminate any unnecessary asymmetries. This platform was made with a thick rubber sole to maximize friction and stepping smoothness. To match the weight difference, lead weights were glued to a stand in the middle of the support platform. The dimensional specification of the opposite leg support platform can be viewed in appendix E.

Figure 36: Platform used to compensate for the height of the GEMS

3.8 : CAD Model Verification

A SolidWorks 3D CAD model was created and altered as the GEMS design progressed. This CAD model was used for spacial and dimensional predictive purposes as well as the creation of technical drawings conveniently used for custom manufacture of shoe components. This model made it very simple to create any changes, troubleshoot any dimensional issues, and predict issues for any proposed components or changes. Figure 37 shows snapshots of the final SolidWorks 3D CAD model.

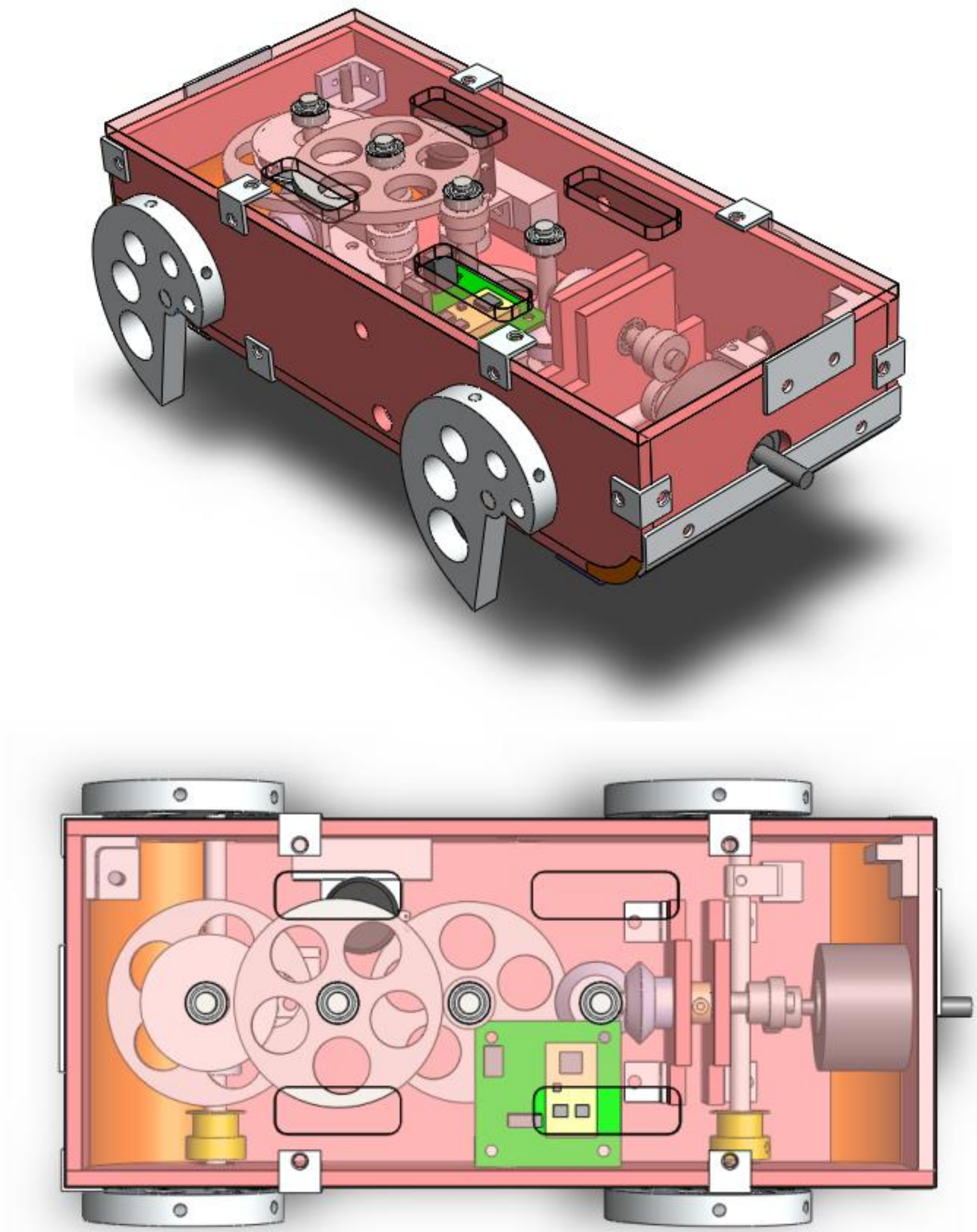

Figure 37: GEMS SolidWorks 3D CAD model

Chapter 4 : Results

The assembled and functioning GEMS is shown in Figure 38 and in Figure 39. Although not a complete motion analysis was performed on the GEMS, the completed GEMS was evaluated by wearing it for walking on it three to four steps at a time. By doing this an effective horizontal push length was measured and the GEMS movements were observed. An effective way to describe the resulting GEMS is to compare it to the initial criteria outlined in chapter 1.

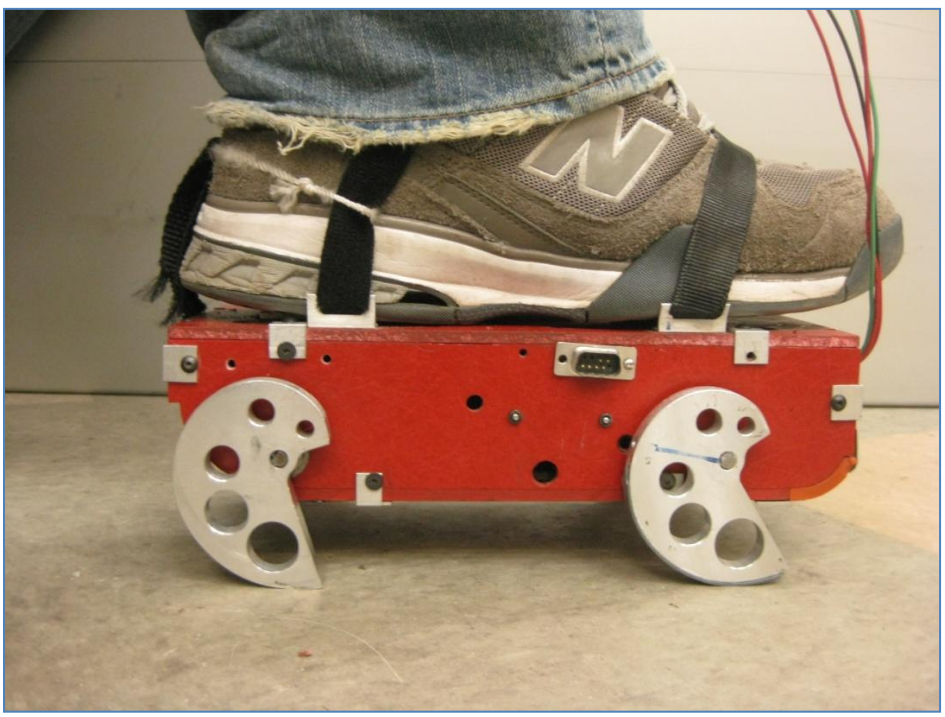

Figure 38: Complete GEMS strapped to user's foot

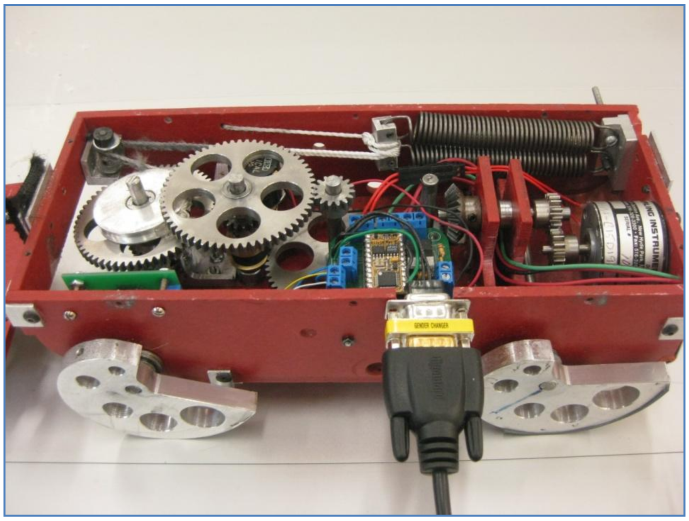

Figure 39: Interior of complete GEMS

1. *Total weight:* The final GEMS has a total weight of 4.5lb (2kg). Majority of this weight is contributed by the magnetic particle brake, spur gears and miter gears in the gear train, and the fiberglass frame. Although this new GEMS design alleviates the major problem of the last GEMS in that it moves smooth and controllable, it is too heavy and requires optimization in that sense. For reference, an average everyday shoe weighs in the range of two to three pounds

2. *Strength:* Although the new GEMS becomes unreliable when a person of 115 kg proceeds to walk on it, it succeeds in withholding all static and dynamic forces exerted by a 90 kg person during walking.

3. *Generated motion:* The finished GEMS generates a backwards motion of 15.2 cm each step. This backward distance of 15.2 cm successfully mimics half of the full backward motion generated by split belt gait rehabilitation research. Placing a similar GEMS design with wheels generating a forward progression

on the opposite foot instead of the support platform would successfully generate a relative 30.4 cm. This motion is smooth and controlled and is depicted in Figure 40.

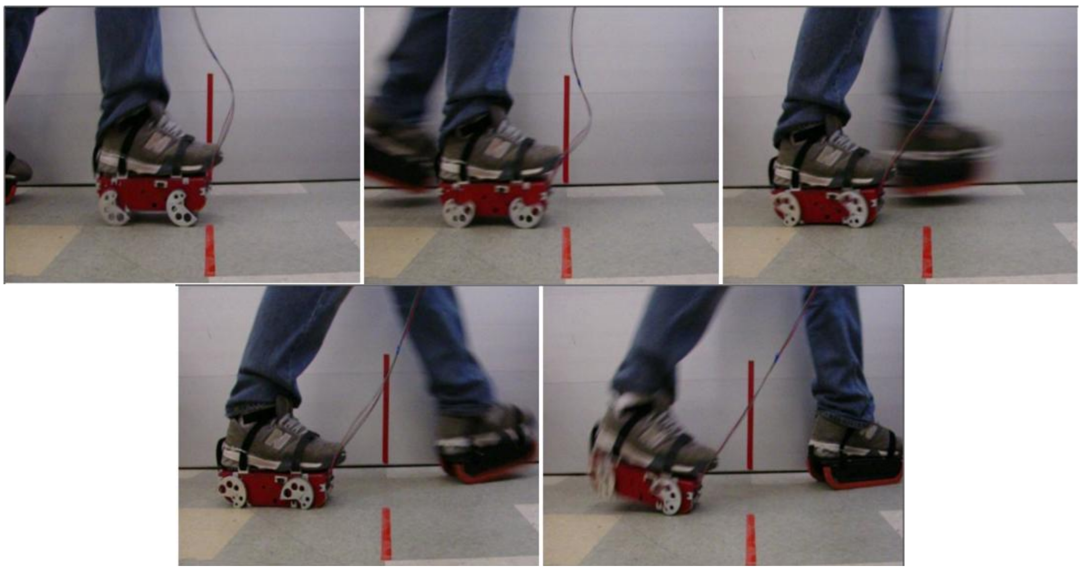

Figure 40: GEMS stepping motion. Note that each floor tile is 12in (30.5cm)

4. *Consistent motion:* While the first GEMS prototype worked well in that it generated a backward motion, it had great variability in each step. Not only could each step be shorter or longer, the backward velocity at which the foot was pushed back could be different at each step and with each person. This variability easily activates the user's balancing and restoration reflexes and seems unnatural. This problem was solved with the new GEMS design in that reduced shoe movement variability by consistently using the same resistance on each step with a controlled magnetic particle brake. While initial tests looked promising in the sense of reducing GEMS variability during each step, further

gait analysis with the GEMS is required to draw a stable conclusion about the long term performance of the shoe.

5. *Portability:* The new GEMS, as the old GEMS, is completely portable and can be worn on any hard surface such as carpet, concrete, or floor tiles. It is also powered by a light battery pack worn on the user's hip.

6. *Time to recharge:* The new GEMS prototype utilizes a battery that exceeds prior design criteria of lasting 1.5 hours, it is estimated to last 4.5 hours. However, the new GEMS was not completely tested over that time span and further investigation is necessary.

7. *Size (height):* The height of the new GEMS does not meet the proposed height criteria of 2.5in and has a final height of 3.8in. The major components that cause this height are the gear train and the wheels. Placing the gear train on the inside of the frame naturally yields a frame height equal the gear train height while the initial height of the wheels account for the rest of the height.

8. *Size (width):* Since none of the components significantly influence the shoe width, the GEMS has a 4.375in frame width and a 5.375in width including wheels. This GEMS prototype meets the proposed width criteria.

9. *Size (length):* The length criteria is met by the new GEMS design with a length of 10.375in. While it satisfies the criteria of an average sized tennis shoe, the length is the result of the gear train and the magnetic particle brake imbedded inside the GEMS frame.

10. *Cost-effectiveness:* The finished new GEMS and the previous GEMS do not currently meet this criteria in that both are custom made designs made from various custom components and include extensive manual labor. Neither shoe was optimized for manufacture.

11. *Shoe Progression:* The GEMS successfully utilizes four wheels in the shape of an Archimedean spiral. This wheel uses the user's downward force and redirects it to a backward motion. This wheel shape should allow a total push distance of the shoe of at least 6.5in (15cm).

12. *Straps:* The same shoe strapping technique that was used in the previous GEMS was utilized in the new GEMS design allowing minimal movement between the GEMS and the user's foot.

13. *Opposite Foot Support Platform:* Because of the height difference between he GEMS and the opposite foot which sits on the ground, a foot platform of the same height and weight was constructed. It successfully mimics the same height, width, length, and weight of the second GEMS prototype.

Table 4 shows the summery of the above criteria and how the first and second GEMS prototypes have or have not met them.

Table 4: New and old GEMS compared by criteria

	1	2	3	4	5	6	7	8	9	10	11	12	13
New GEMS	N	Y	Y	Y	Y	Y	N	Y	Y	N	Y	Y	Y
Previous GEMS	Y	Y	Y	N	Y	Y	N	Y	Y	N	*N/A*	Y	*N/A*

Chapter 5 : Future Work

Even though many drawbacks of the previous design were corrected there are numerous improvement opportunities in the design. Such improvements and optimization include in the following areas:

- *Material selection* – This is a big category for improvement from the new GEMS design. While many current material design decisions are reasonable, more investigation in how different materials can benefit with different components is necessary.
- *Wheel transition* - Adding a middle point of contact between the front and back axle is needed to alleviate an abrupt transition between the two points of contact with the ground
- *Balancing of forces* - Balancing the forces between the gear train, magnetic particle brake, wheel shape, frictional forces, and reset mechanism is also a major category of improvement and optimization. These four GEMS components very much affect each other and determine the properties of each other. For instance, the shape of the wheel determines how much torque at what instance of the gait cycle is generated while the magnetic particle brake and the gear train is to be designed in such a way to where they can resist this generated torque.
- *Wheel Shape* - The Archimedean spiral wheel shape alone is an interesting and agile aspect of the GEMS and is open to a detailed analysis, possibly resulting in shaping the wheel in such a way where desired horizontal forces are produced at

specific instances of rotation. Further investigation on how to utilize a more useful wheel shape exerting desired forces at specific instances is needed.

- *Frame design* – The current GEMS used a standard rectangular boxed frame design made out of fiberglass. The frame can easily be optimized not only in shape but also in weight by carefully designing a skeletal type shape frame with various material components.
- *Gear train layout* – The gear train is a vital part of the current GEMS design and needs further attention in how it is laid out. Different types of gear train layouts can be considered, including one where the gear train sits partially outside the shoe shape.

Furthermore, the GEMS as developed is sufficient enough for test trials revealing if in fact this design can affect more positive gait altering effects than the previous version and comparable to previous split belt research.

Chapter 6 : Conclusions

I successfully designed and constructed a functioning gait enhancing mobile shoe (GEMS). Although the previous version of the GEMS effectively showed some after-effects in the wearer's gait comparable to previous split belt rehabilitation studies, it was unnaturally jerky pushing the wearer's foot back in a sudden motion analogous to slipping on ice. This type of sudden motion triggers a person's recovery and balancing instincts, thus producing an unnatural feel. This unnatural motion was greatly reduced in this version of the motion controlled GEMS model.

My improved model is easily adjustable to different horizontal push length, force, speed and direction by simply adjusting the wheel size, wheel shape, and magnetic particle brake resistance. This adjustability in behavior of the GEMS makes testing for various situations possible.

While this new design of the GEMS is promising and is a step forward from the previous GEMS design, room for optimization are plentiful. These optimizations include, but are not limited to, material selection, wheel shape design, control shoe resistance design, or reset mechanism design.

Furthermore, during the design and assembly process of this new GEMS many practical and technical missteps were taken from which valuable GEMS design skills were acquired for proceeding versions of the GEMS. These missteps range anywhere from machining practices to design approach strategies.

All in all the new GEMS design is successful in satisfying most of the initially proposed design criteria and giving more insight in its design process.

References

[1] A. Groot, R. Decker, K. Reed. Gait Enhancing Mobile Shoe (GEMS) for Rehabilitation. Third Erophaptics Conference and Symposium on Haptic Interfaces for Virtual Enviroment and Teleoperator Systems. March 18-20, 2009.

[2] D. Reisman, R. Wityk, and A. Bastian. Split-belt treadmill walking adaptation in post-stroke hemiparesis. J. Neurologic Physical Therapy, 29:196, 2005.

[3] T. Lam, M. Anderschitz, and V. Dietz. Contribution of feedback and feedforward strategies to locomotor adaptations. J. Neurophysiol, 95:766–773, 2006.

[4] S. Morton and A. Bastian. Cerebellar Contributions to Locomotor Adaptations during Splitbelt Treadmill Walking. J. Neurosci., 26(36):9107–9116, 2006.

[5] Lam T, Wolstenholme C, and Yang JF. How do infants adapt to loading of the limb during the swing phase of stepping? J Neurophysiol 89: 1920– 1928, 2003.

[6] R. Grasso, L. Bianchi, and F. Lacquaniti. Motor Patterns for Human Gait: Backward Versus Forward Locomotion. J. Neurophysiol, 80(4):1868–1885, 1998

[7] J. Perry. 1992. Gait Analysis: Normal and Pathological Function. Thorofare, NJ: Slack Inc

[8] P. Perkins and M. Wilson. Slip resistance testing of shoes – new developments. Ergonomics, 26(1):73–82, 1983.

[9] Whittle, M. W.,1991. Gait Analysis: An introduction. Butterworth-Heinemann Ltd, Oxford.

[10] R. Keamey. Context dependence of intrinsic and reflex contributions to ankle stiffness. In Proc. of 1st International IEEE EMBS Conf. on Neural Engineering, pages 434–437, March 2003.

[11] A. Gordon, G. Westling, K. Cole, and R. Johansson. Memory representations underlying motor commands used during manipulation of common and novel objects. J. Neurophysiol, 69(6):1789–1796, 1993.

[12] J. Krakauer, M. Ghilardi, and G. Ghez. Independent learning of internal models for kinematic and dynamic control of reaching. Nature Neuroscience, 2:1026–1031, 1999.

[13] Lou JS and Bloedel JR. A new conditioning paradigm: conditioned limb movements in locomoting decerebrate ferrets. s 84: 185–190, 1988.

[14] Hodgson JA, Roy RR, de Leon R, Dobkin B, and Edgerton VR. Can the mammalian lumbar spinal cord learn a motor task? Med Sci Sports Exerc 26: 1491–1497, 1994.

[15] Timoszyk WK, De Leon RD, London N, Roy RR, Edgerton VR, and Reinkensmeyer DJ. The rat lumbosacral spinal cord adapts to robotic loading applied during stance. J Neurophysiol 88: 3108–3117, 2002

[16] Arshavsky YI, Orlovsky GN, Panchin YV, Roberts A, Soffe SR (1993) Neuronal control of swimming locomotion: analysis of the pteropod mollusk Clione and embryos of the amphibian Xenopus. Trends Neurosci 16:227–233.

[17] Yanagihara D, Kondo I. Nitric oxide plays a key role in adaptive control of locomotion in cat. Proc Natl Acad Sci USA 1996; 93: 13292–7.

[18] D. Reinkensmeyer, J. Emken, and S. Cramer. Robotics, motor learning, and neurologic recovery. Annu. Rev. Biomed. Eng., 6:497– 525, 2004.

[19] H. Schmidt, S. Hesse, R. Bernhardt, and J. Kr¨uger. HapticWalker - a novel haptic foot device. ACM Trans. on Applied Perception, 2(2):166–180, 2005.

[20] M. Otis, C. du Tremblay, F. De Rainville, M. Mokhtari, D. Laurendeau, and C. Gosselin. Hybrid control with multi-contact interactions for 6 DOF haptic foot platform on a cable-driven locomotion interface. In Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems, pages 161–168, March 2008.

[21] D. Reisman, R. Wityk, K. Silver, and A. Bastian. Locomotor adaptation on a split-belt treadmill can improve walking symmetry post-stroke. Brain, 130(7):1861–1872, 2007

[22] G. I. Turnbull, J. C. Wall. Long-term changes in hemiplegic gait. Gait & Posture. Vol. 3: 258-261, December 1995

[23] Bohannon R W, Andrews A W, Smith M B. Rehabilitation goals of patients with hemiplegia. Inl J Rehabil Res 1988; II:181-183.

[24] M. H. Woollacott. Posture and Gait from Newborn to Elderly. Posture and Gait: Proceeding of the 9th Int. Symp on Postural and Gait Research, Marseille, France, 29 May – 1 June 1988

[25] M. H. Granat, D.J. Maxwell, C.J. Bosch, A.C.B. Ferguson, K.R. Lees and J.C. Barbenel. A body-worn gait analysis system for evaluating hemiplegic gait. Med. Eng. Phys. Vol. 17, No. 5, pp. 390-394, 1995

[26] Kirtiey, C., Whittle, M.W. and Jefferson, R.J. Influence of walking speed on gait parameters. J Biomed Eng 1985, 7,282-288

[27] Georgia Southern University. Vicon Camera [Online] Available http://chhs.georgiasouthern.edu/hk/images/ath-pics/current-students/ViconCamera.JPG. March 14, 2011

[28] Lab Safety Supply. Conductive Mat. [Online] Available http://www.labsafety.com/images/xl/WEARWELL-Electrically-Conductive-Mats-LSS-_i_LBV31604_01.jpg, March 14, 2011

[29] Wall, J.C., Dhanendran, M. and Klenerman, L. A method of measuring the temporal/distance factors of gait. Biomed Engng 1976, 11, 409-412

[30] Wall, J.C., Charteris, J. and Hoare, J.W. An automated on-line system for measuring the temporal patterns of foot/floor contact. J Med Eng Tech 1978, 2, 187-190

[31] Wall JC, Turnbull GI. Gait asymmetries in residual hemiplegia. Arch Phys Med Rehabil 67:550–553, 1986

[32] Lin PY, Yang YR, Cheng SJ, Wang RY. The relation between ankle impairments and gait velocity andb symmetry in people with stroke. Arch Phys Med Rehabil 87:562–568, 2006

[33] Plotnik M, Giladi N, Balash Y, Peretz C, Hausdorff JM. Is freezing of gait in Parkinson's disease related to asymmetric motor function? Ann Neurol 57:656–663, 2005

[34] Marder E, Calabrese RL. Principles of rhythmic motor pattern generation. Physiol Rev 76:687–717, 1996

[35] Grillner S. Control of locomotion in bipeds, tetrapods and fish. In: Brookhardt J, Mountcastle G (eds) Handbook of physiology. American Physiological Society, Bethesda, pp 1179–1236, 1981

[36] Yang YR, Chen YC, Lee CS, Cheng SJ, Wang RY, Dualtask- related gait changes in individuals with stroke. Gait Posture [Epub ahead of print], 2006

[37] Jensen L, Prokop T, Dietz V (1998) Adaptational effects during human split-belt walking: influence of afferent input. Exp Brain Res 118:126–130

[38] M. Gaviria et al. Plantar dynamics of hemiplegic gait: A Methodological Approach. Gait & Posture 297-307, 1996

[39] Monco Medical. Split-Belt Treadmill. [Online] Available http://www.alibaba.com/ productfree/262579915/Medical_Research_Treadmills /showimage. html, March, 14, 2011.

[40] K. L. Bunday, A. M. Bronstein. Visuo-Vestibular Influences involved in the 'Broken Escalator' gait aftereffect. Gait & Posture, Volume 21, June 2005, Page S23.

[41] Wikipedia. Vicon Camera [Online] Available http://upload.wikimedia.org/wikipedia/commons/4/42/Copenhagen_Metro_escalators.jpg. March 22, 2011

Appendices

Appendix A: GEMS Electrical Diagram

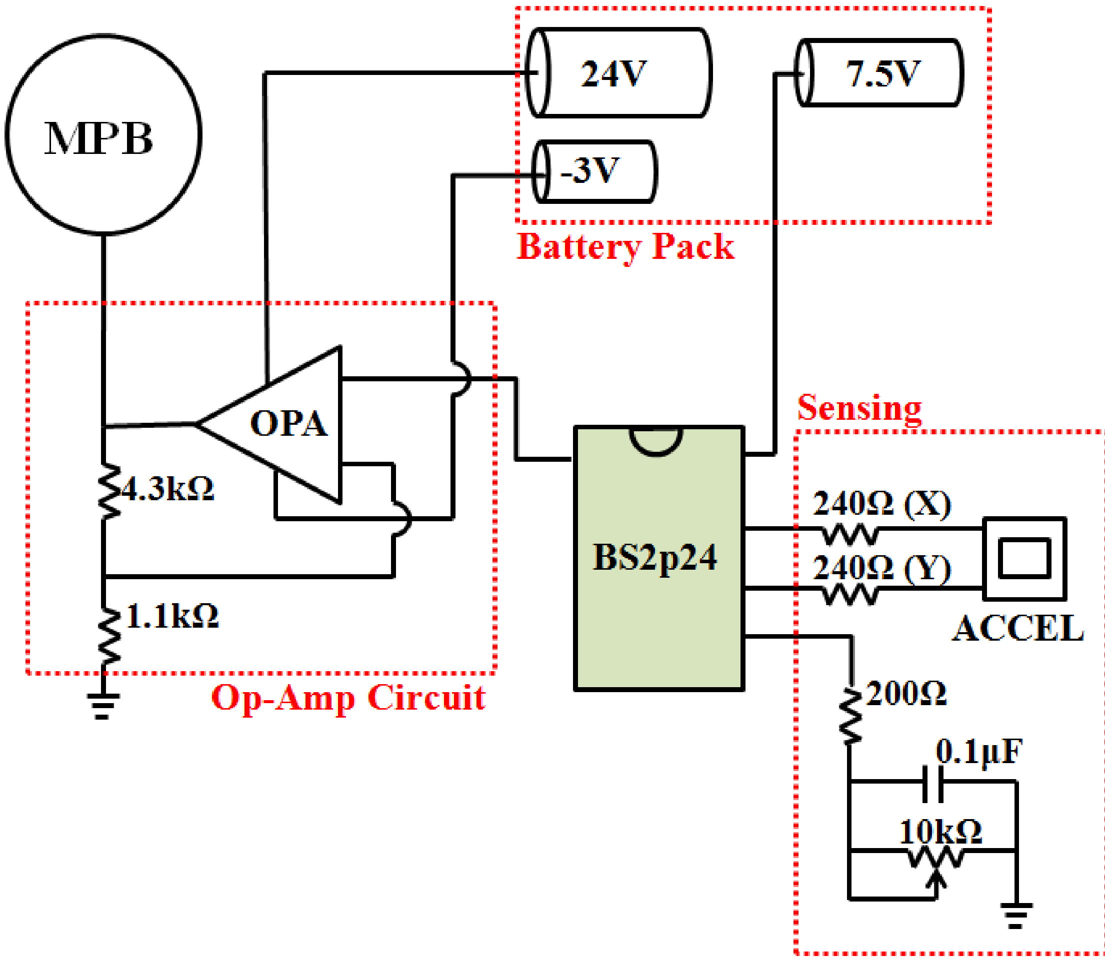

Figure A1: GEMS Electrical Diagram

Appendix B: Pugh Analysis: GEMS Frame Material

Criteria:		
1	Light and Ridgid	
2	Easy and fast to machine	
3	Maximum 3/16" thick	
4	Withstands dynamic gait forces with box shape	
5	Fairly fatigue resistant	
Material Option:	Acrlilic	Aluminum
	ABS	Steel
	Acetal	Fiberglass
	PEEK	

	1	**2**	**3**	**4**	**5**	
Multiplier:	**x1**	**x1**	**x1**	**x2**	**x1**	**Total**
Acrlilic	x	x	x			3
ABS	x	x	x			3
Acetal	x	x	x		x	4
PEEK	x	x	x			3
Aluminum	x		x	x		4
Steel	*too heavy*					-
Fiberglass	x		x	x	x	**5**

Fiberglass with possible aluminum pieces is used.

Figure B1: Pugh Analysis: GEMS frame material

Appendix C: Archimedean Spiral Wheel Shape Selection Tool

Wheel Parameters		
a	0.75	
b	0.007	
n	1.07	
Shortest R	**0.75**	**in**
Longest R	**2.06**	**in**
Area	**5.24**	**in^2**
Thickness	**0.25**	**in**
Density	**0.05**	**lb/in^3**
Perimeter	**6.867**	**in**
Weight	**0.065**	**lb**
Number of Wheels with Ground Contact:	**2**	
Total Vertical Forcel:	**800**	**N**
Avg Hor. Force per whee	**134.5**	**N**
St. Dev	49.56	N
% St. Dev	37%	N
Total Avg Hor Force:	***269.0***	***N***
Avg Torque per wheel:	**40.1**	**lb-in**
St. Dev	10.87	lb-in
% St. Dev	0.27	lb-in
Total Avg Torque:	***80.2***	***lb-in***

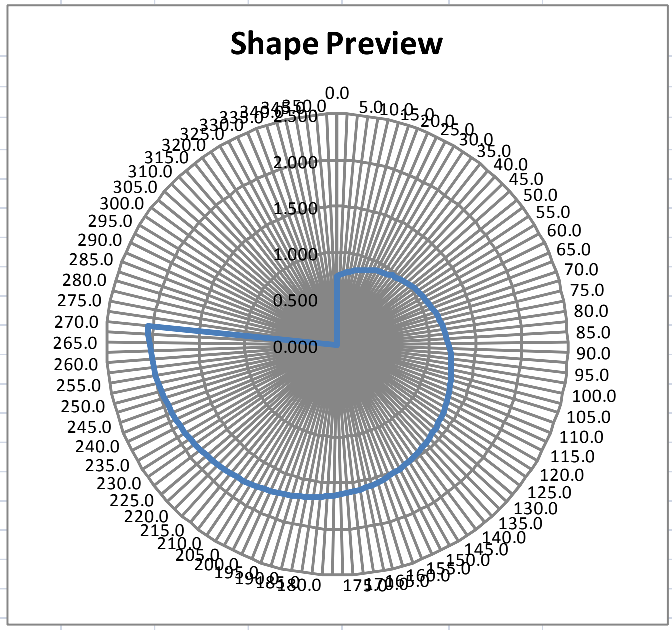

Figure C1: Archimedean Spiral wheel shape selection tool

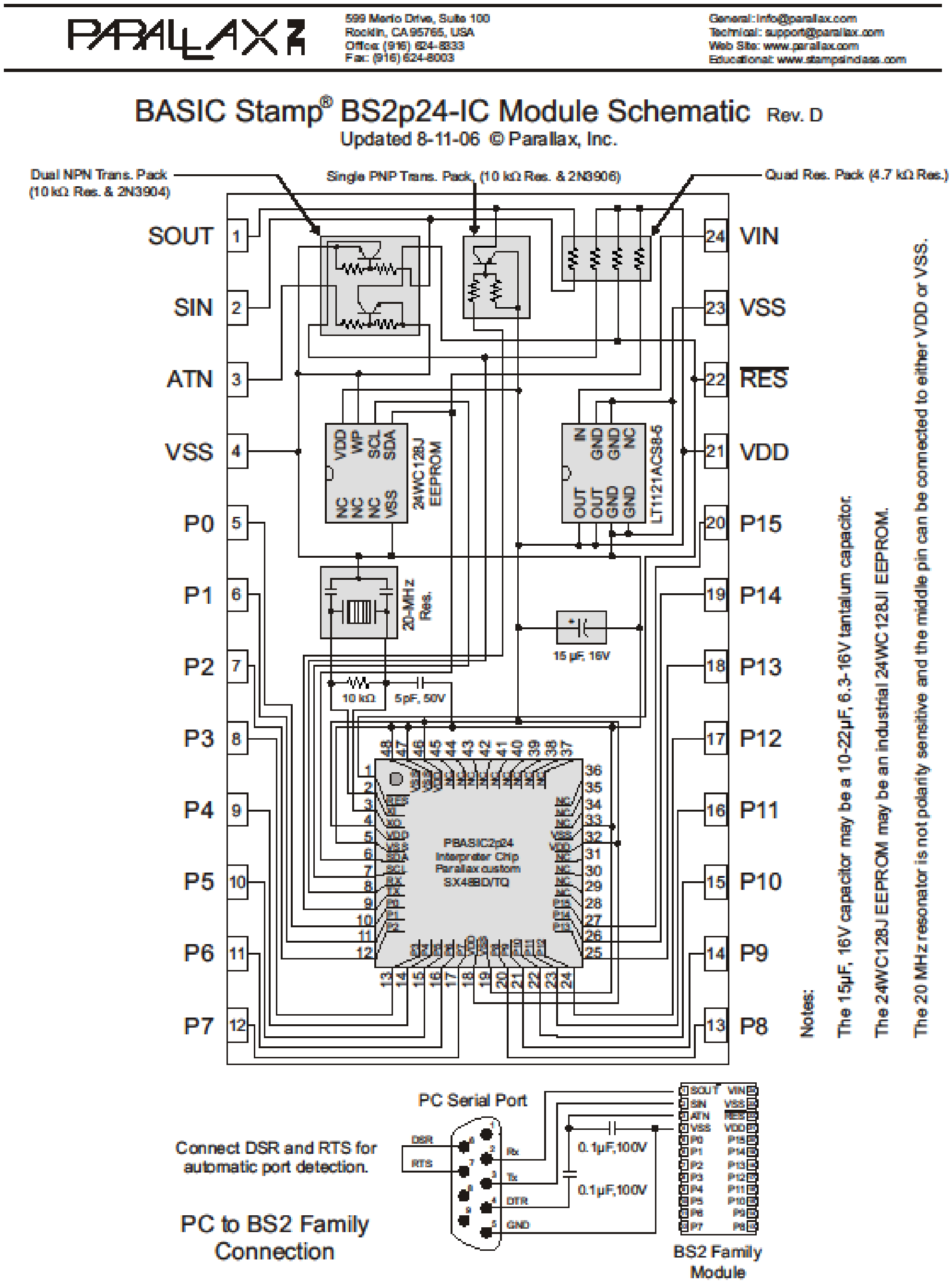

Figure D1: BS2p24 module schematic

Appendix D: (Continued)

Table D1: BS2p24 Microcontroller specification

Released Products	BS2p24-IC
Package	24-pin DIP
Package Size (L x W x H)	1.2" x 0.6" x 0.4"
Environment *	0º - 70º C (32º - 158º F)
Microcontroller	Ubicom SX48AC
Processor Speed	20 MHz Turbo
Program Execution Speed	~12,000 instructions/sec.
RAM Size	38 Bytes (12 I/O, 26 Variable)
Scratch Pad RAM	128 Bytes
EEPROM (Program) Size	8 x 2K Bytes, ~4,000 inst.
Number of I/O pins	16 + 2 Dedicated Serial
Voltage Requirements	5 - 12 vdc
Current Draw @ 5V	40 mA Run / 350 µA Sleep
Source / Sink Current per I/O	30 mA / 30 mA
Source / Sink Current per unit	60 mA / 60 mA per 8 I/O pins
PBASIC Commands***	61
PC Programming Interface	Serial (9600 baud)
Windows Text Editor	Stampw.exe (v1.1 and up)

PARALLAX

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Sales: sales@parallax.com
Technical: support@parallax.com

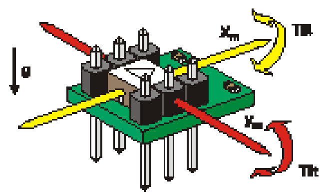
Office: (916) 624-8333
Fax: (916) 624-8003
Sales: (888) 512-1024
Tech Support: (888) 997-8267

Memsic 2125 Dual-Axis Accelerometer (#28017)

The Memsic 2125 is a low-cost thermal accelerometer capable of measuring tilt, collision, static and dynamic acceleration, rotation, and vibration with a range of ±3 g on two axes. Memsic provides the 2125 IC in a surface-mount format. Parallax mounts the circuit on a tiny PCB providing all I/O connections so it can easily be inserted on a breadboard or through-hole prototype area.

Features

- Measures ±3 g on each axis
- Simple pulse output of g-force for each axis
- Convenient 6-pin 0.1" spacing DIP module
- Analog output of temperature (TOut pin)
- Fully temperature compensated over 0 to 70 °C operating temperature range



Key Specifications

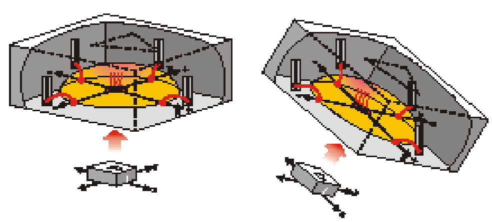
- Power Requirements: 3.3 to 5 VDC; < 5 mA supply current
- Communication: TTL/CMOS compatible 100 Hz PWM output signal with duty cycle proportional to acceleration
- Dimensions: 0.42 x 0.42 x 0.45 in (10.7 x 10.7 x 11.8 mm)
- Operating temperature: 32 to 158 °F (0 to 70 °C)

Application Ideas

- Dual-axis tilt and acceleration sensing for autonomous robot navigation
- R/C tilt controller or autopilot
- Tilt-sensing Human Interface Device
- Motion/lack-of-motion sensor for alarm system
- Single-axis rotational angle and position sensing

Theory of Operation

The MX2125 has a chamber of gas with a heating element in the center and four temperature sensors around its edge. When the accelerometer is level, the hot gas pocket rises to the top-center of the chamber, and all the sensors will measure the same temperature.



By tilting the accelerometer, the hot gas will collect closer to some of temperature sensors. By comparing the sensor temperatures, both static acceleration (gravity and tilt) and dynamic acceleration (like taking a ride in a car) can be detected. The MX2125 converts the temperature measurements into signals (pulse durations) that are easy for microcontrollers to measure and decipher.

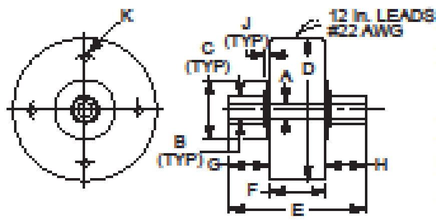
Figure D2: Accelerometer specifications

Appendix D: (Continued)

Magnetic Particle Brakes

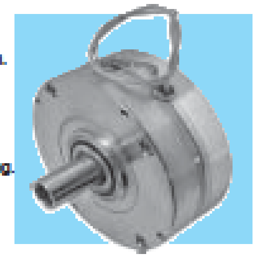
Stock Drive Products/Sterling Instrument

■ ZERO BACKLASH ■ LOW INERTIA ■ NO FRICTION SURFACE



The shaft becomes coupled to the housing with electrical excitation. The torque is proportional to the D.C. input current.

Typical applications are: tensioning, controlled stops, positioning, locking and motor testing. Voltages other than 24 Volts D.C. available on special order.



• 24 VOLTS D.C.

Catalog Number	A +.001 -.000	B ±.0002	C +.000 -.001	D ±.016	E ±.01	F ±.03	G ±.02	H ±.02	J ±.01	K
◊S90MPA-B11D12S	Solid	.1247	.437	1.05	2.50	.88	.81	.81	.06	* 6 ea. #1-72 on .906 BC
◊S90MPA-B16D18S		.1872	.687	1.56	2.70	1.06	.81	.81	.06	* 3 ea. #6-32 on 1.350 BC
S90MPA-B21D25S		.2496	.750	2.09	3.05	1.15	.94	.94	.06	3 ea. #6-32 on 1.350 BC
S90MPA-B26D37S		.3746	1.186	2.47	3.56	1.37	1.09	1.09	.08	3 ea. #6-32 on 2.203 BC
S90MPA-B28D37S S90MPA-B28D37H38	Solid .375	.3746 .498	1.125	2.87	3.56 2.10	1.37	1.09 .47	1.09 .27	.08	3 ea. #8-32 on 2.000 BC
S90MPA-B34D50S S90MPA-B34D50H38	Solid .375	.4995 .498	1.125	3.37	3.72 2.20	1.47	1.12 .47	1.12 .25	.09	4 ea. #10-32 on 3.000 BC
** S90MPA-B45D75S S90MPA-B45D75H50	Solid .501	.7495 .748	1.875	4.50	3.53 2.63	1.77	1.42 .52	.33	.11	4 ea. #10-32 on 4.228 BC
S90MPA-B47D75S S90MPA-B47D75H50	Solid .501	.7495 .748	1.875	4.71	3.53 2.63	1.77	1.41 .52	.33	.11	4 ea. #10-32 on 4.228 BC
S90MPA-B52D75S S90MPA-B52D75H75	Solid .750	.7495 .906	▲1.625 3.187	5.23	3.92 3.25	2.17	1.53 .82	.22 .26	.13 .09	4 ea. 1/4-20 on 4.812 BC

*One side only ▲ 3.187 on H side **3/16 keyway & flat, 90° oriented in respect to the keyway on the end of the shaft.
◊Supplied with housing solder terminals with leads attached.

SPECIFICATIONS

Catalog Number	Torque Range lb. in.	Elect. Power watts	Shaft Inertia lb. in. sec.²	Max. Speed rpm	Mech. Heat Dissipation watts	Max. Overhung Load lb.	Unforced Response msec.	Weight lb.
S90MPA-B11D12S	.006 - .3	1.5	16×10^{-8}	3500	2	.7	6	.2
S90MPA-B16D18S	.04 - 1	2	11×10^{-7}	3000	3.5	4	8	.5
S90MPA-B21D25S	.08 - 2.5	3	55×10^{-7}	2500	8	5	9	1
S90MPA-B25D37S	.3 - 6	4.5	23×10^{-6}	2000	15	25	20	1.5
S90MPA-B28D37S S90MPA-B28D37H38	.3 - 15	6	34×10^{-6}	2000	20	25	25	2.5
S90MPA-B34D50S S90MPA-B34D50H38	.6 - 35	9	12×10^{-5}	1800	30	50	35	4
S90MPA-B45D75S S90MPA-B45D75H50	1 - 60	8	45×10^{-5}	1800	50	100	85	7
S90MPA-B47D75S S90MPA-B47D75H50	2.5 - 115	13	61×10^{-5}	1800	55	120	90	8
S90MPA-B52D75S S90MPA-B52D75H75	3 - 150	13	15×10^{-4}	1300	80	120	130	12

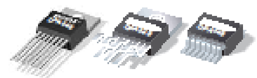
NOTE: All models are available with the shaft on one end, on special order.

REV: 6-3-05 mm 13-28

Figure D3: Magnetic particle brake specifications

Burr-Brown Products from Texas Instruments

OPA548



SBOS070B – OCTOBER 1997 – OCTOBER 2003

High-Voltage, High-Current OPERATIONAL AMPLIFIER

FEATURES

- **WIDE SUPPLY RANGE**
  Single Supply: +8V to +60V
  Dual Supply: ±4V to ±30V
- **HIGH OUTPUT CURRENT:**
  3A Continuous
  5A Peak
- **WIDE OUTPUT VOLTAGE SWING**
- **FULLY PROTECTED:**
  Thermal Shutdown
  Adjustable Current Limit
- **OUTPUT DISABLE CONTROL**
- **THERMAL SHUTDOWN INDICATOR**
- **HIGH SLEW RATE: 10V/µs**
- **LOW QUIESCENT CURRENT**
- **PACKAGES:**
  7-Lead TO-220, Zip and Straight Leads
  7-Lead DDPAK Surface-Mount

APPLICATIONS

- **VALVE, ACTUATOR DRIVERS**
- **SYNCHRO, SERVO DRIVERS**
- **POWER SUPPLIES**
- **TEST EQUIPMENT**
- **TRANSDUCER EXCITATION**
- **AUDIO AMPLIFIERS**

DESCRIPTION

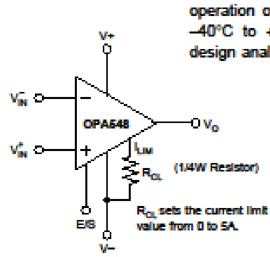
The OPA548 is a low-cost, high-voltage/high-current operational amplifier ideal for driving a wide variety of loads. A laser-trimmed monolithic integrated circuit provides excellent low-level signal accuracy and high output voltage and current.

The OPA548 operates from either single or dual supplies for design flexibility. In single-supply operation, the input common-mode range extends below ground.

The OPA548 is internally protected against over-temperature conditions and current overloads. In addition, the OPA548 was designed to provide an accurate, user-selected current limit. Unlike other designs which use a "power" resistor in series with the output current path, the OPA548 senses the load indirectly. This allows the current limit to be adjusted from 0A to 5A with a resistor/potentiometer or controlled digitally with a voltage-out or current-out DAC.

The Enable/Status (E/S) pin provides two functions. An input on the pin not only disables the output stage to effectively disconnect the load, but also reduces the quiescent current to conserve power. The E/S pin output can be monitored to determine if the OPA548 is in thermal shutdown.

The OPA548 is available in an industry-standard 7-lead staggered and straight lead TO-220 package, and a 7-lead DDPAK surface-mount plastic power package. The copper tab allows easy mounting to a heat sink or circuit board for excellent thermal performance. It is specified for operation over the extended industrial temperature range, –40°C to +85°C. A SPICE macromodel is available for design analysis.



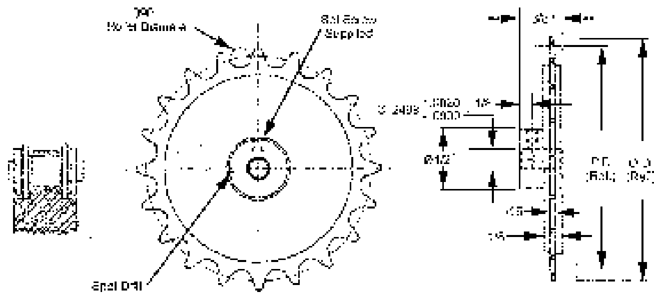
Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.

Figure D4: Op-Amp specifications

Appendix D: (Continued)

SPROCKETS

CIR. PITCH	BORE	STYLE	MATERIALS	BERG'S ® NAME	CHAIN
.1475	1/4"	PIN HUB	303 Stainless Steel Or 2024-T4 Aluminum Anodized	ROW-L-ER®	Operates with RC14SS Series



303 STAINLESS STEEL	2024T4 ALUMINUM ANODIZED			
STOCK NO.	STOCK NO.	NO. OF TEETH	PITCH DIA.	OUTSIDE DIA.
14EM26S-14	14EM26A-14	14•	.663	.714
14EM26S-15	14EM26A-15	15	.709	.761
14EM26S-16	14EM26A-16	16	.756	.808
14EM26S-17	14EM26A-17	17	.803	.854
14EM26S-18	14EM26A-18	18	.849	.901
14EM26S-19	14EM26A-19	19	.896	.948
14EM26S-20	14EM26A-20	20	.943	.994
14EM26S-21	14EM26A-21	21	.990	1.041
14EM26S-22	14EM26A-22	22	1.036	1.088
14EM26S-23	14EM26A-23	23	1.083	1.135
14EM26S-24	14EM26A-24	24	1.130	1.182
14EM26S-25	14EM26A-25	25	1.177	1.228
14EM26S-26	14EM26A-26	26	1.224	1.275
14EM26S-27	14EM26A-27	27	1.271	1.322
14EM26S-28	14EM26A-28	28	1.317	1.369
14EM26S-29	14EM26A-29	29	1.364	1.416
14EM26S-30	14EM26A-30	30	1.411	1.463
14EM26S-31	14EM26A-31	31	1.458	1.510
14EM26S-32	14EM26A-32	32	1.505	1.556
14EM26S-33	14EM26A-33	33	1.552	1.603
14EM26S-34	14EM26A-34	34	1.599	1.650
14EM26S-35	14EM26A-35	35	1.646	1.679
14EM26S-36	14EM26A-36	36	1.692	1.744
14EM26S-38	14EM26A-38	38	1.786	1.838
14EM26S-40	14EM26A-40	40	1.880	1.932
14EM26S-42	14EM26A-42	42	1.974	2.025
14EM26S-44	14EM26A-44	44	2.068	2.119

• For 14 teeth, hub diameter equals .47.
Other Bore sizes and other numbers of teeth are available on request.

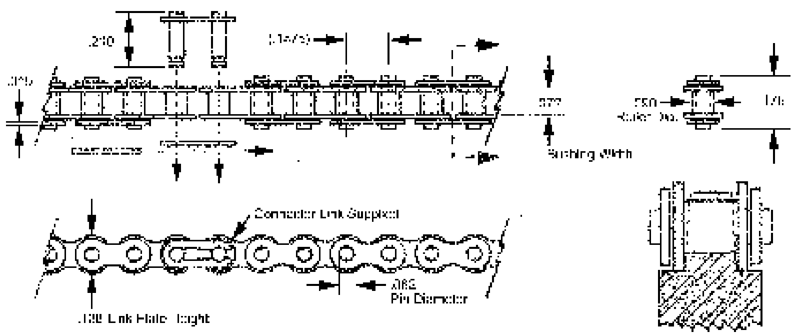
Teeth could be anodized.

1-800-232-BERG A 100 WWW.WMBERG.COM

Figure D5: Sprocket connecting front and back GEMS axle

LINK CHAIN

CIRCULAR PITCH	ROLLER DIAMETER	BERG NAME	MATERIAL	SPROCKET
.1475	.090	ROW-L-ER®	Stainless Steel, Non-Magnetic, Prestretched Single Strand	Operates with 14EM and 14SP series.



STOCK NO.	NO. OF PITCHES	LENGTH INCHES
RC14SS-40	40	5.900
RC14SS-50	50	7.375
RC14SS-60	60	8.850
RC14SS-70	70	10.325
RC14SS-80	80	11.800
RC14SS-90	90	13.275
RC14SS-100	100	14.750
RC14SS-110	110	16.225
RC14SS-120	120	17.700
RC14SS-130	130	19.175
RC14SS-140	140	20.650
RC14SS-150	150	22.125
RC14SS-160	160	23.600
RC14SS-170	170	25.075
RC14SS-180	180	26.550
RC14SS-190	190	28.025
RC14SS-200	200	29.500
RC14SS-210	210	30.975
RC14SS-220	220	32.450
RC14SS-230	230	33.925
RC14SS-240	240	35.400
RC14SS-250	250	36.875
RC14SS-260	260	38.350
RC14SS-270	270	39.825
RC14SS-280	280	41.300
RC14SS-290	290	42.775
RC14SS-300	300	44.250
RC14SS-310	310	45.725
RC14SS-320	320	47.200
RC14SS-330	330	48.675
RC14SS-340	340	50.150
RC14SS-350	350	51.625
RC14SS-360	360	53.100
RC14SS-370	370	54.575
RC14SS-380	380	56.050
RC14SS-390	390	57.524

* Maximum recommended operating load is for a slip fit connecting link, which is standard. A press fit connecting link is a special available on request.

Special lengths available on request (only even numbers of links).

Maximum recommended Operating Load = 20 lbs.*

Ultimate Tensile Strength = 180 lbs.

.035lbs/foot - Must be lubricated.

Use Connector Link Berg P/N RC14SS-CL.

STOCK NO.	LENGTH
RC14SS-5FT	5FT
RC14SS-10FT	10FT
RC14SS-25FT	25FT
RC14SS-50FT	50FT
RC14SS-100FT	100FT

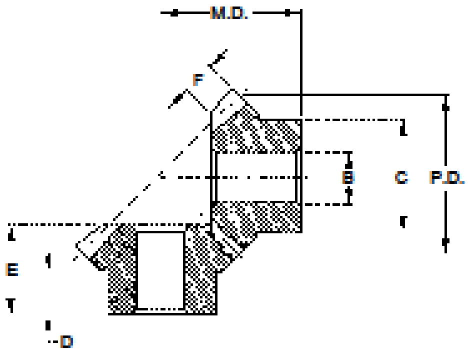
1-800-232-BERG A 96 WWW.WMBERG.COM

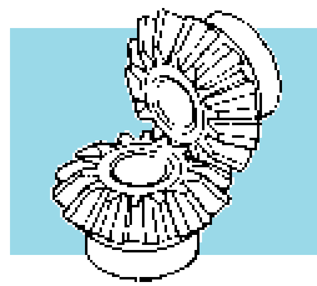
Figure D6: Chain connecting front and back GEMS axle

Appendix D: (Continued)

INCH — **Miter Gears - 48, 32, 24 & 20 Pitch**

■ 20° PRESSURE ANGLE





GEARS 1

MATERIAL: Brass

Catalog Number	Pitch	No. of Teeth	P.D.	B Bore +.0002 -.0006	F Face Width	E Length	C Hub Dia.	D Hub Proj.	M.D. Dim.
A 1B 4-Y48015	48	15	.313	.1250	3/32	7/32	1/4	1/8	.312
A 1B 4-Y48018		18	.375		5/64	9/32	5/16	3/16	.406
A 1B 4-Y32016	32	16	.500	.1875	1/8	11/32	13/32	3/16	.500
A 1B 4-Y32024		24	.750		5/32	27/64	1/2	1/4	.688
A 1B 4-Y24024	24	24	1.000	.2500	7/32	9/16	5/8	9/32	.906
A 1B 4-Y24030		30	1.250	.2500	1/4	37/64	5/8	5/16	1.031
A 1B 4-Y24036		36	1.500	.3125	1/4	39/64	11/16	5/16	1.188

MATERIAL: Steel

Catalog Number	Pitch	No. of Teeth	P.D.	B Bore +.0002 -.0006	F Face Width	E Length	C Hub Dia.	D Hub Proj.	M.D. Dim.
A 1C 4-Y48018	48	18	.375	.1250	.080	9/32	5/16	3/16	.406
A 1C 4-Y32016	32	16	.500	.1875	.120	11/32	13/32	3/16	.500
A 1C 4-Y32024		24	.750		.140	27/64	1/2	1/4	.688
[illegible]	24	18	.750	.2500	.156	9/16	5/8	3/8	.813
A 1C 4-Y24024		24	1.000		.200			9/32	.906
[illegible]	20	12	.600	.2500	.120	31/64	1/2	5/16	.671
A 1C 4-Y20018		18	.900	.3125	.140	5/8	5/8	13/32	.953
A 1C 4-Y20020		20	1.000	.3750	.234	13/16	3/4	1/2	1.125
A 1C 4-Y20025		25	1.250		.250	3/4	1	7/16	1.188

Gears other than standard stock sizes are available on special order.

1–198

Figure D7: Miter gear in GEMS gear train

Appendix E: Dimensions and Drawings

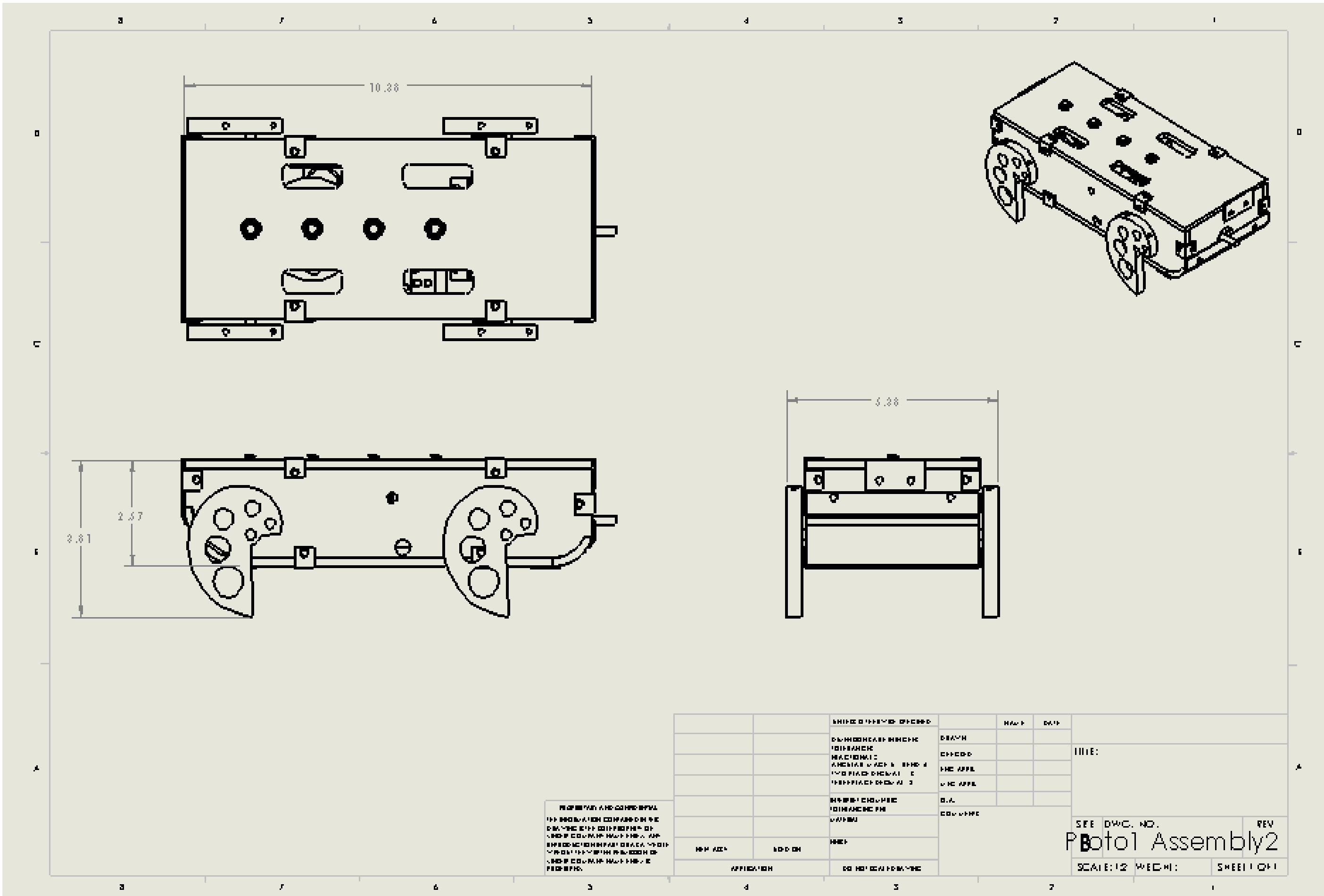


Figure E1: GEMS assembly

Appendix E: (Continued)

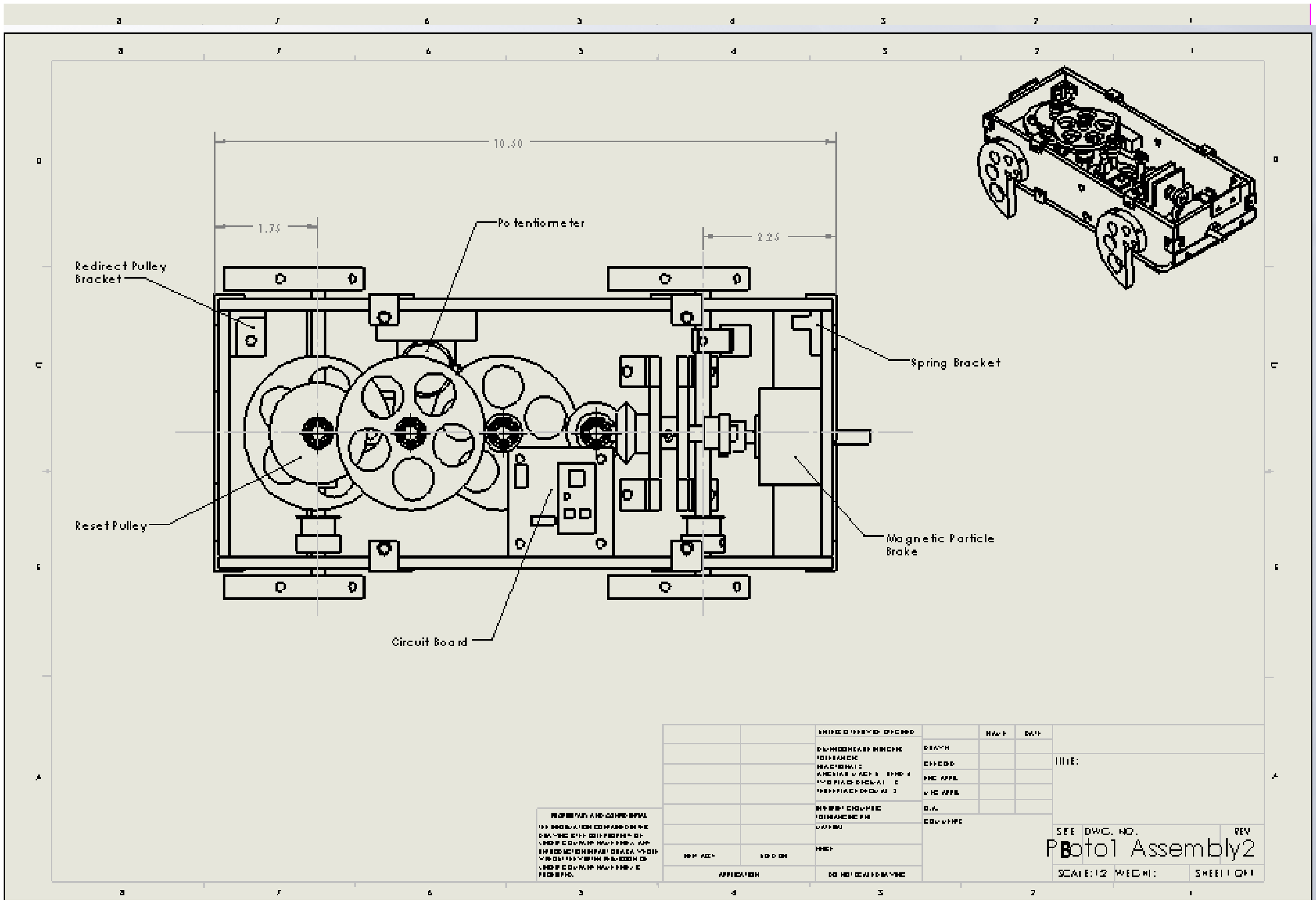


Figure E2: Open GEMS assembly top view

Appendix E: (Continued)

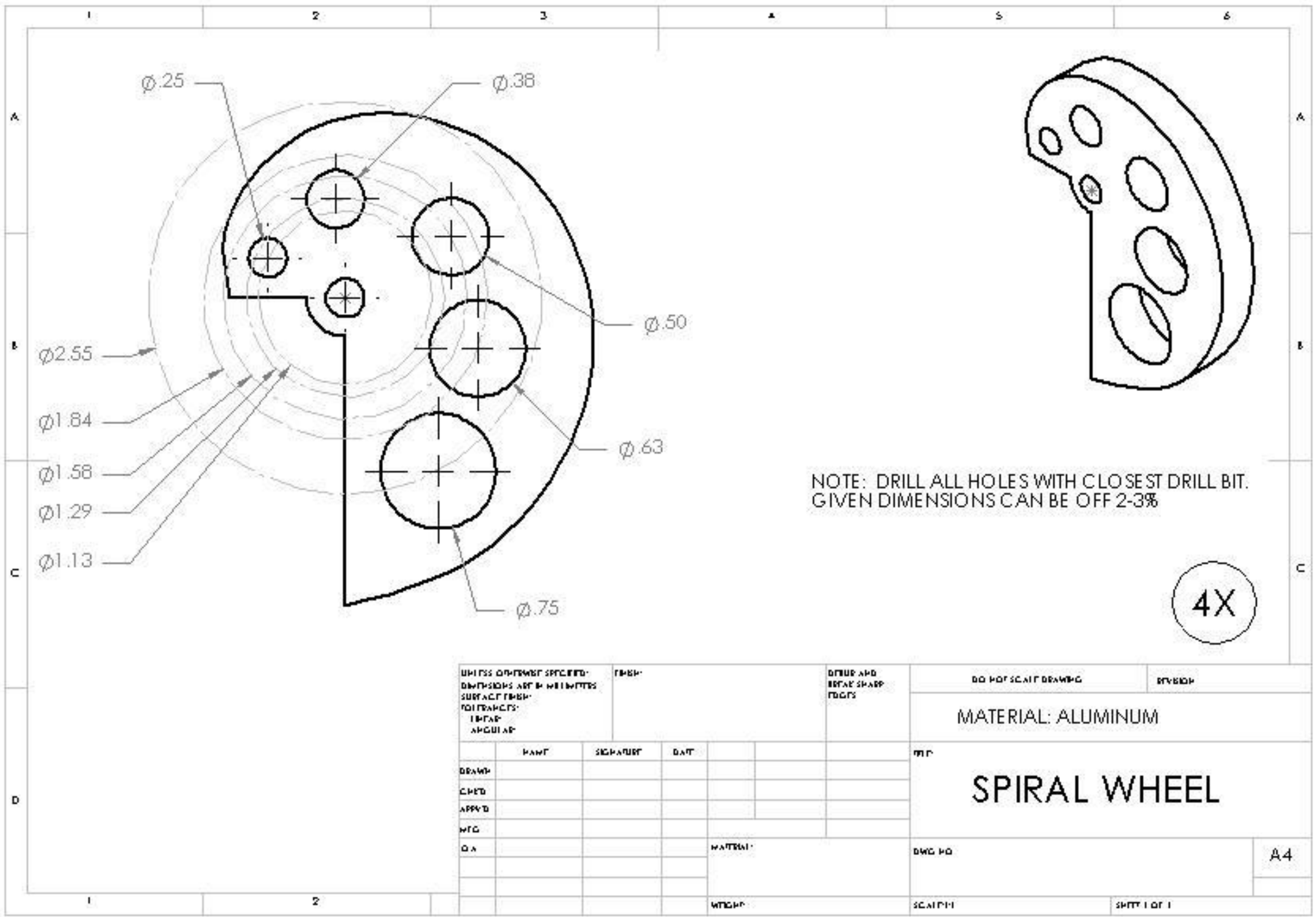


Figure E3: GEMS wheel

Appendix E: (Continued)

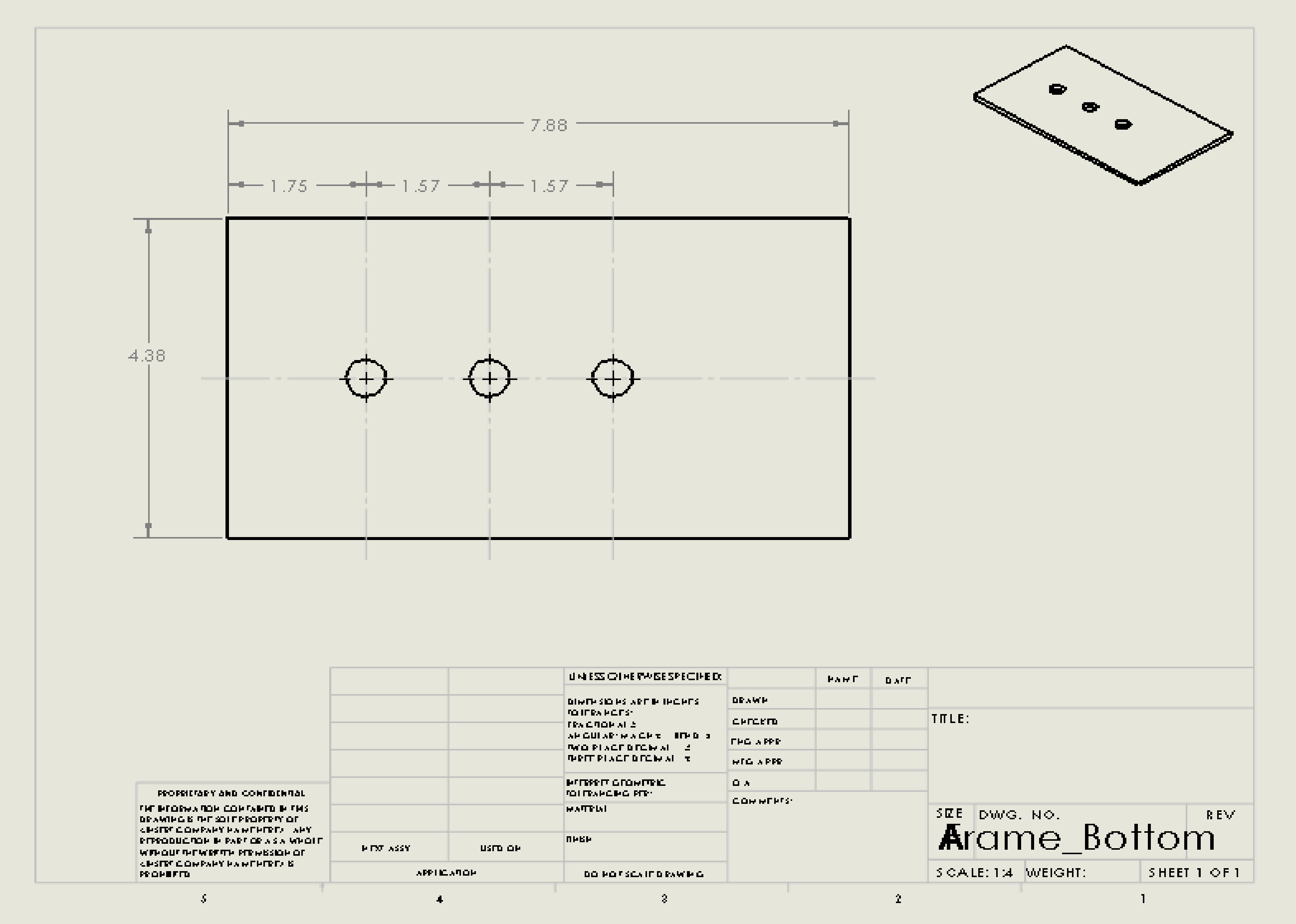


Figure E4: GEMS frame bottom cover

Appendix E: (Continued)

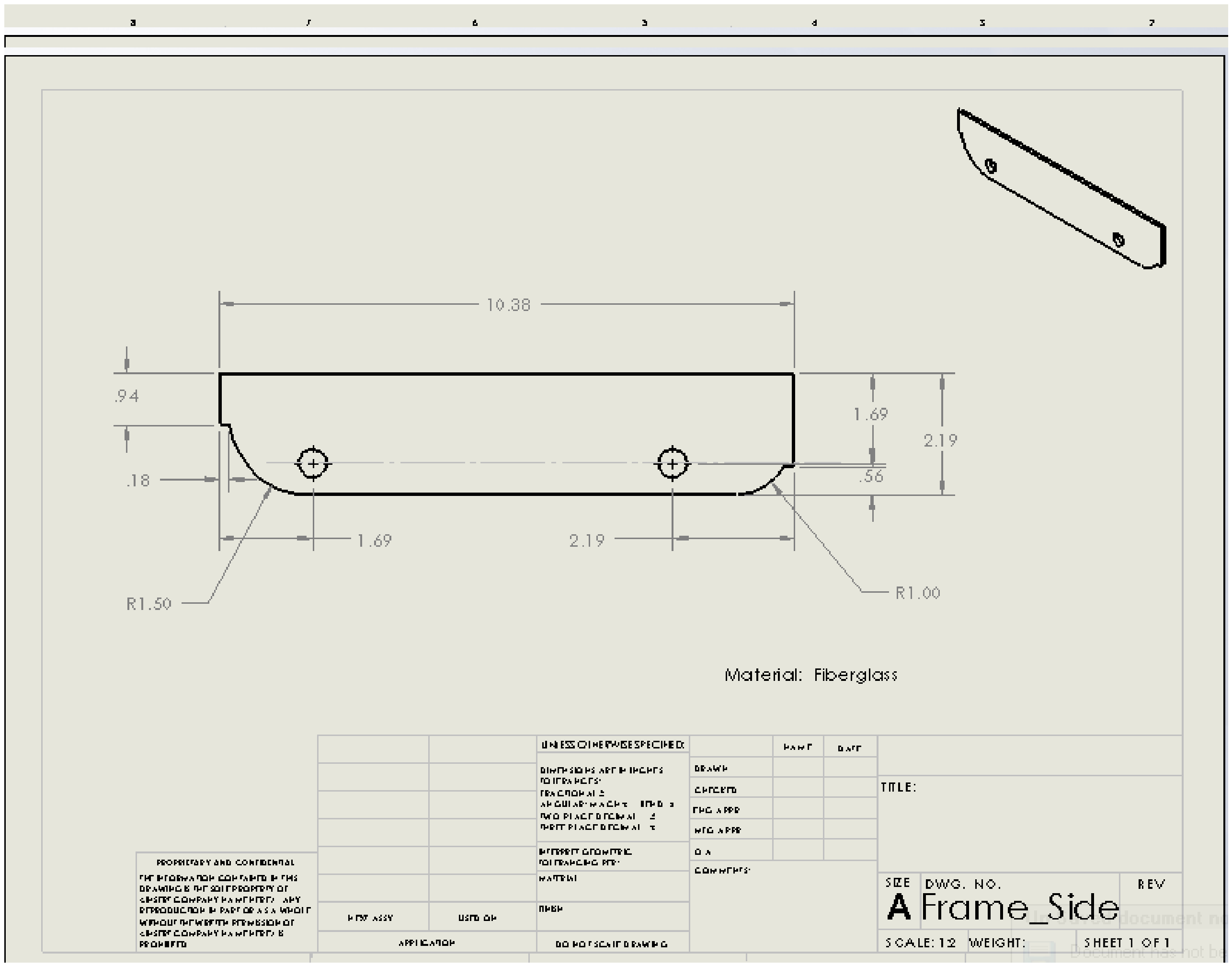


Figure E5: GEMS frame side

Appendix E: (Continued)

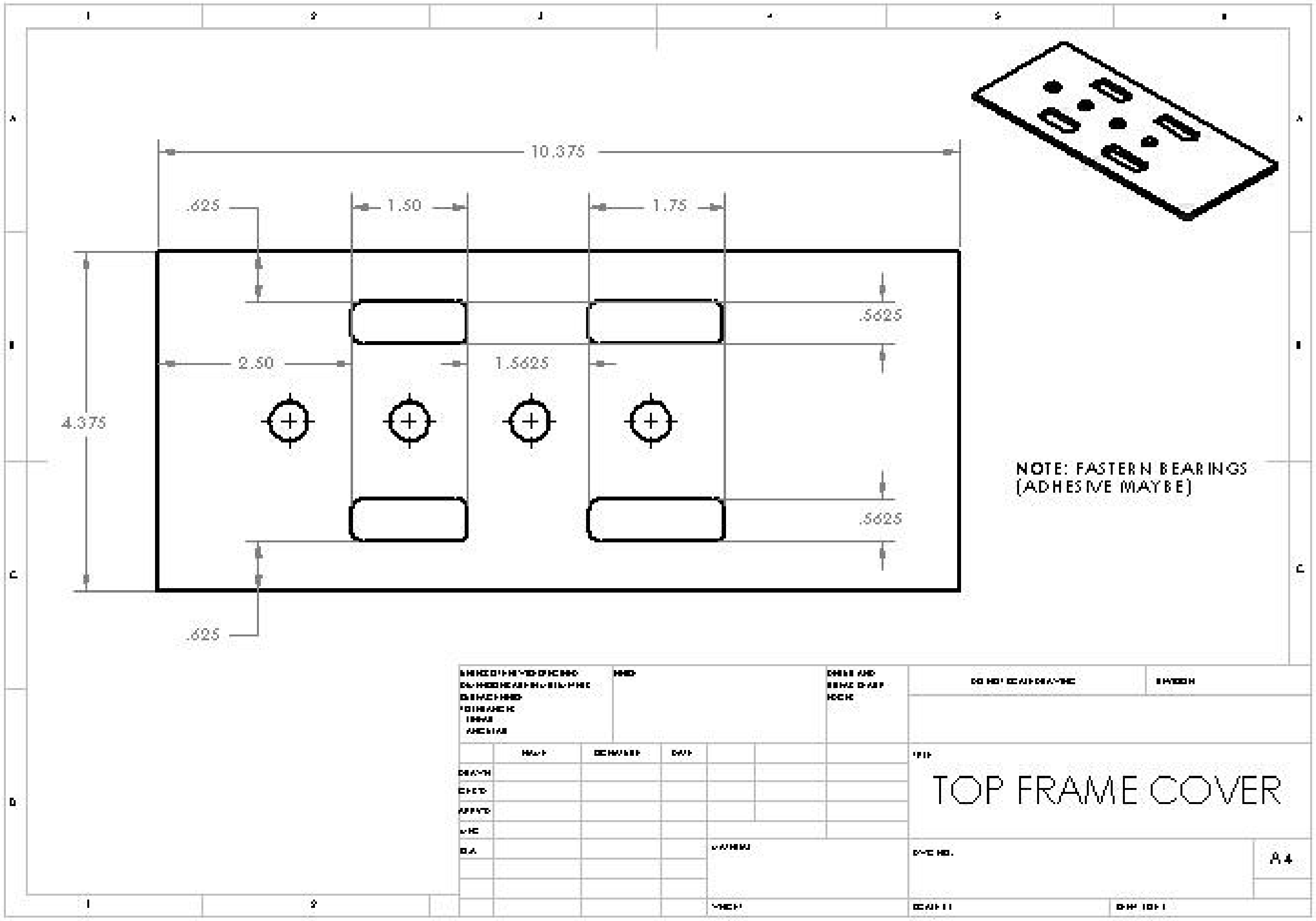


Figure E6: GEMS frame top cover

Appendix E: (Continued)

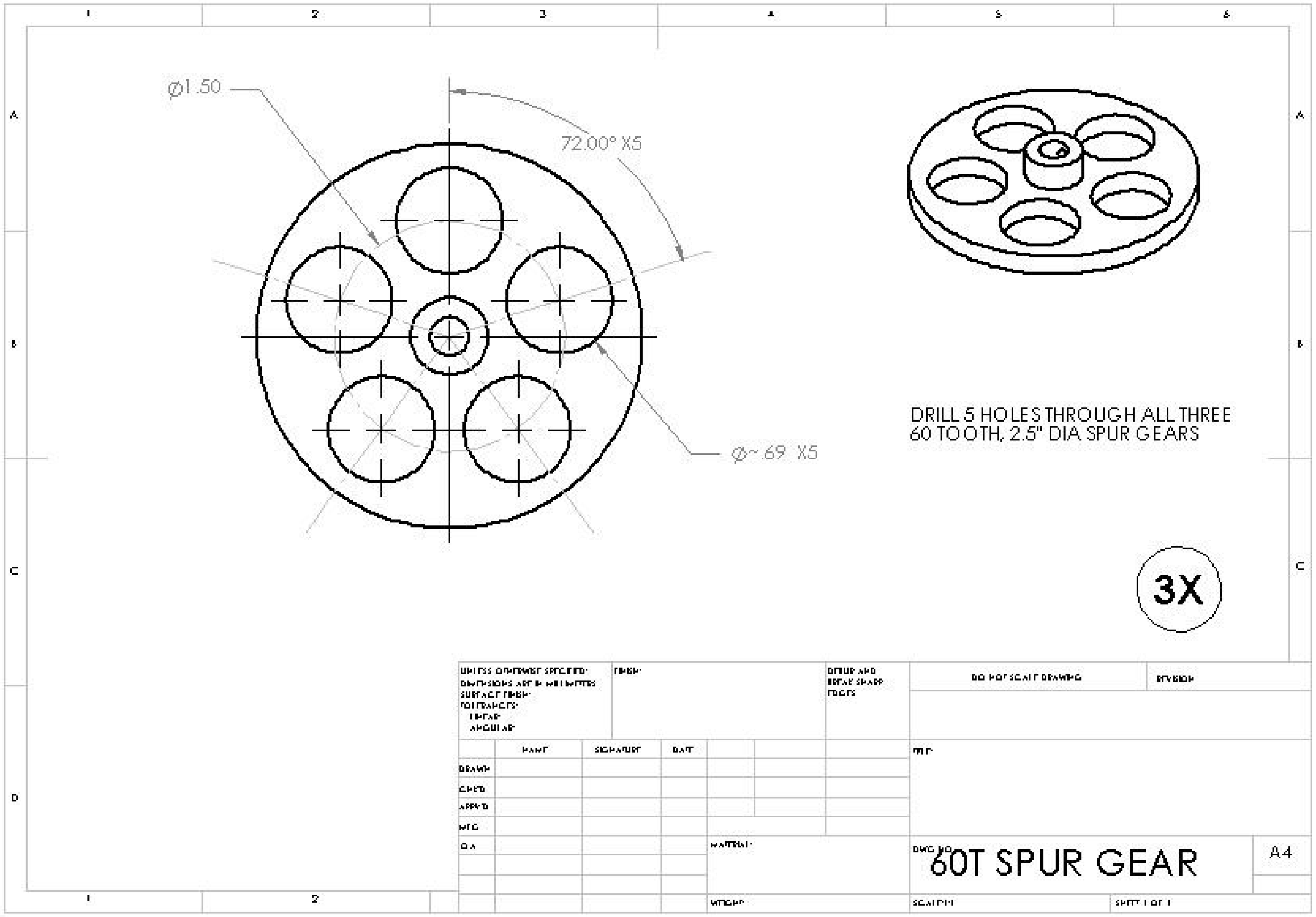


Figure E7: Sixty tooth gear in gear train

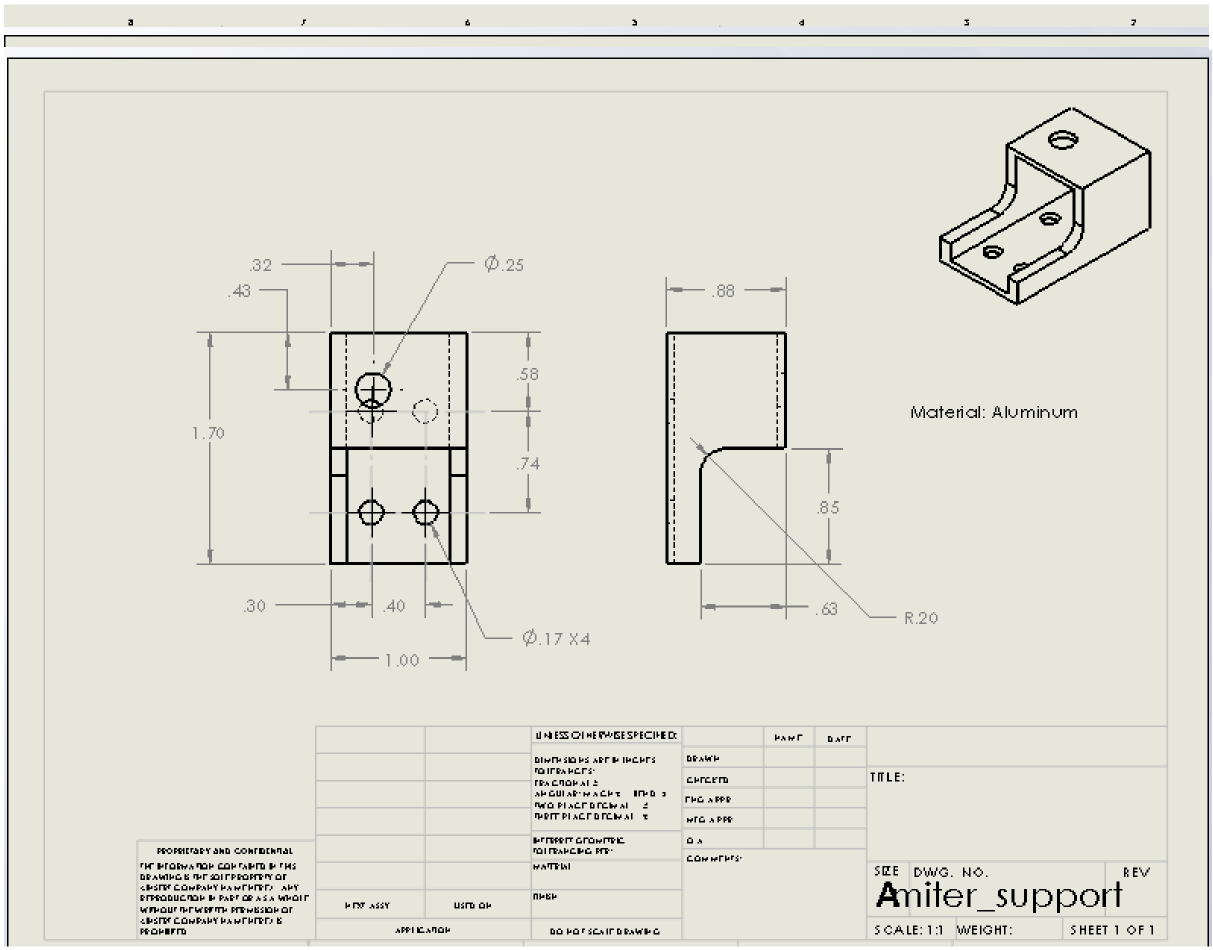


Figure E8: Miter gear bracket

Appendix E: (Continued)

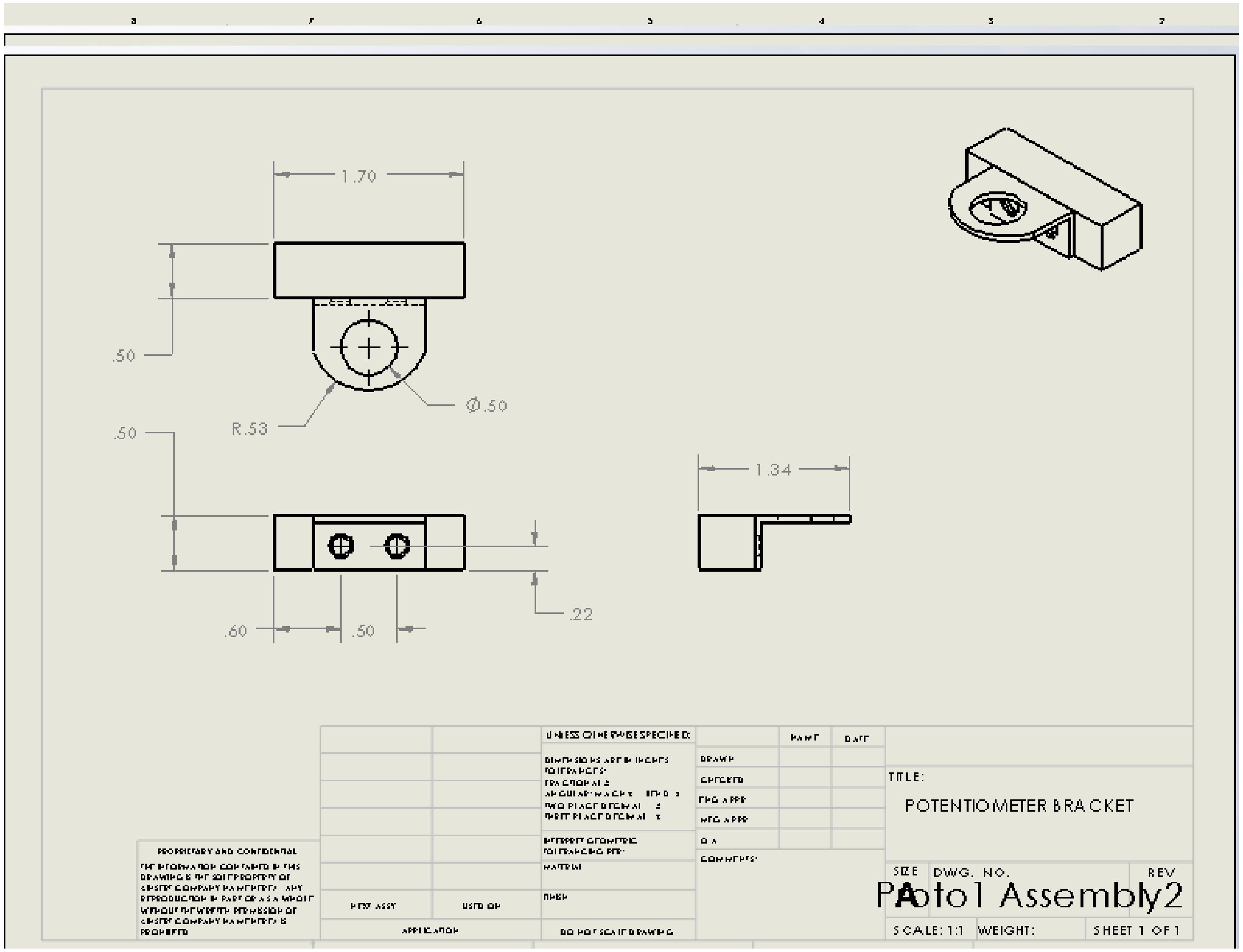


Figure E9: Potentiometer bracket

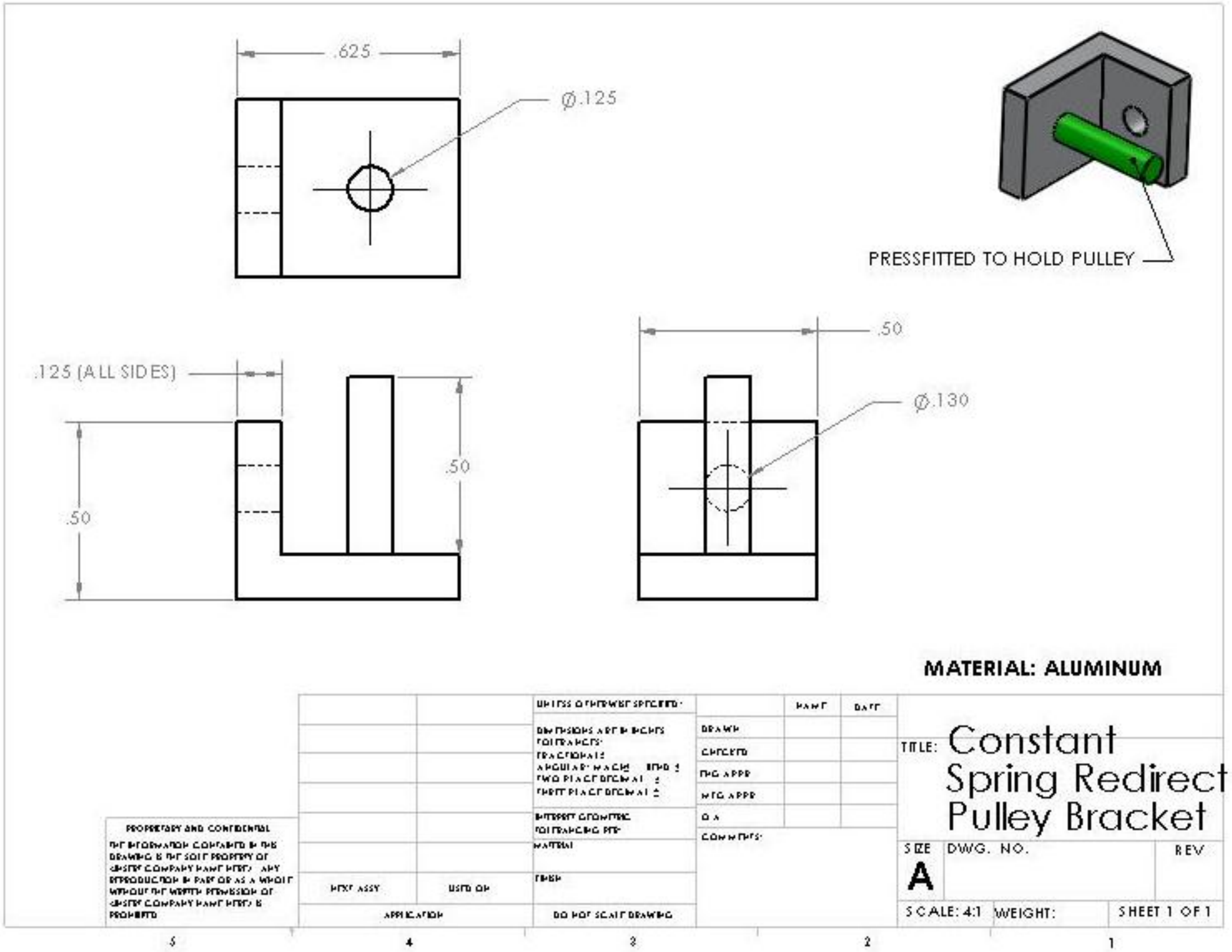


Figure E10: Reset mechanism redirect pulley bracket

Appendix E: (Continued)

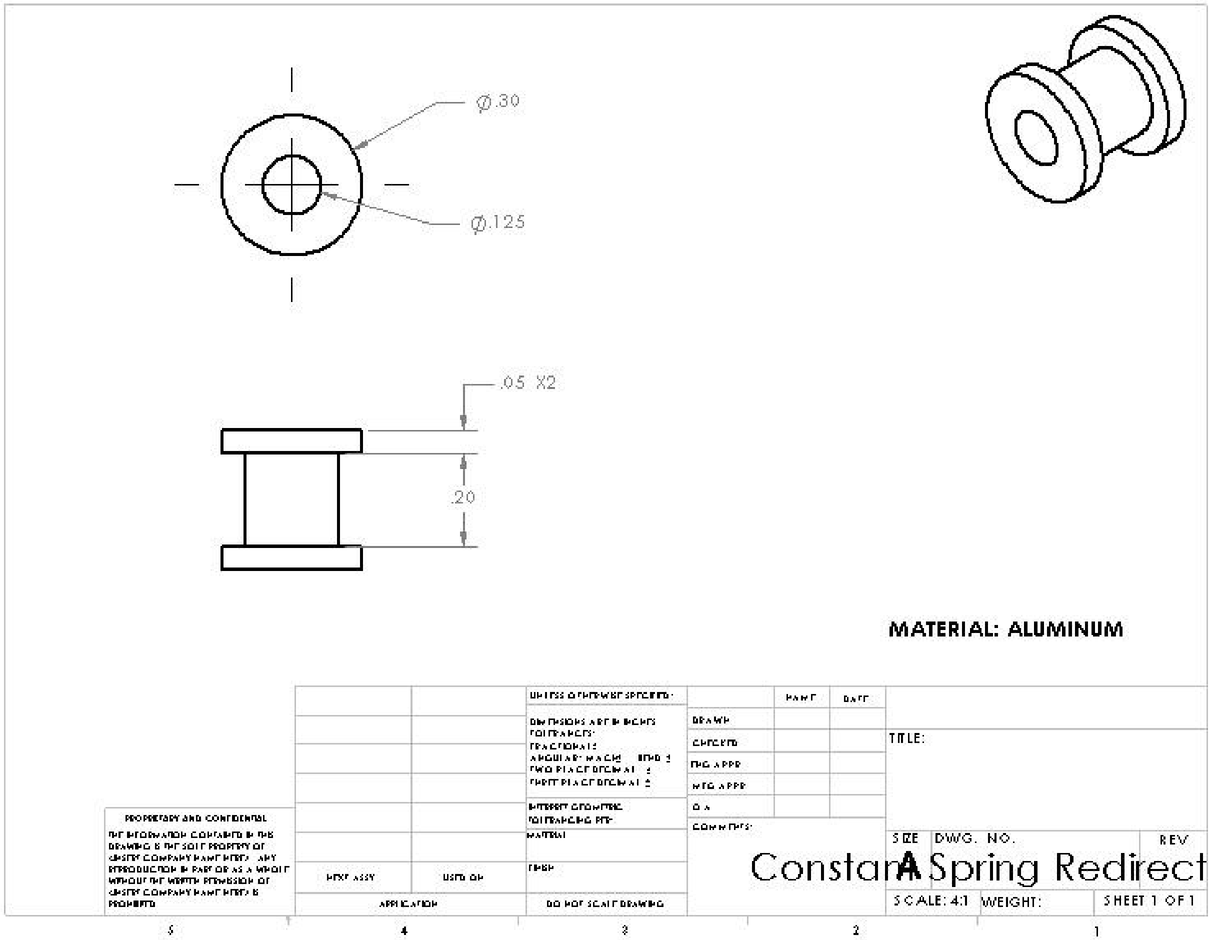


Figure E11: Small reset mechanism pulley

Appendix F: Microcontroller Code

```
                                'ISMET HANDZIC
'Gait Enhancing Mobile Shoe (GEMS) microcontroller PBASIC program
'University of South Florida
'2009 - 2010

' {$STAMP BS2p}
' {$PBASIC 2.5}

CycAdj    CON       $09E    'cycle adjustment for 1 ms
Cycles    CON       60      'FIX PWM VALUE ---  RIGHT NOW:  GOES FROM
1.9V to 1.7V with pot commands

Brake_T   VAR       Word    'Brake torque (0-255  =  0~4.8V = 0~21V)
Brake_T_Byte VAR    Byte
x         VAR       Word    'Accelerometer X direction
phase     VAR       Bit     'Differentiates between wheel rolling or
wheel reseting
x_old          VAR     Word
dX             VAR     Word
dX_max         VAR     Word

Pot_RA              VAR       Word    'Potentiometer rotational angle
value
Pot_RA_D            VAR       Word
Pot_RA_Old          VAR       Word
Pot_RA_D_Old        VAR       Word
Vel_A               VAR       Word
Vel_D               VAR       Word
'P                  VAR       Word
'D                  VAR       Word

RC        PIN       8       'Assign pin 7 as RC Time pin for
Potentiometer

Brake_T = 255               'Brake start off torque (max torque)
Pot_RA_D = 630
x=6700
x_old = 6700
dX_max = 0
phase = 1

Main:
DO


'POTENTIOMETER READING
  HIGH RC                          'charge the cap
  PAUSE 1                          'for 1 ms
  RCTIME RC, 1, Pot_RA             'measure RC discharge time (Pin, 0
or 1 logic, variable)


  IF(Pot_RA < 430)  THEN
    phase = 1  'swing phase
```

```
  ENDIF

  IF(Pot_RA > 580) THEN
    phase = 0  'stance phase
  ENDIF

  IF(phase = 1) THEN
    Brake_T = 0
  ELSE
    Brake_T = 50
  ENDIF

Brake:
'BRAKE TORQUE OUTPUT
IF(Brake_T > 255) THEN
  Brake_T_Byte = 255
ELSE
  Brake_T_Byte = Brake_T
ENDIF

  PWM 15, Brake_T_Byte, (Cycles */ CycAdj) 'PWM Pin, Duty cycle, cyles
                                     'Adjust capasitor charging time
(5*R*C) if needed
                                     'Adjust Cycles value if needed

LOOP

END
```