Northern Illinois University

Cam Controlled Walking Robot

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Capstone Approval Page

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Abstract.

The objective of this project is to create a walking robot employing a cam controlled leg. The cam controlled walker was first theorized in the Master's Thesis of Xiaonan Wan of Northern Illinois University. The principle of a cam controlled is to combine the advantages of both wheels and legs into one manipulator. The robot is constructed of a body with four motor driven walking pods. Each pod consisted of three cam-controlled members. The robot is capable of walking in a smooth, strait and level line, when it is activated. The robot is designed to be less than 69 centimeters and less than 2 kg in mass. The basic pod design involves a rotating slider and a cam shaped track, which causes a rotating member to have an end path that is a level strait line. This design is advantageous because it allows for the level motion of a wheel and the small footprint and rough terrain navigation ability of a leg. Analysis of motion shows that the robot does not move at constant speed. This creates a dynamic loading problem along with a dynamic control problem. The robot is built to be structurally sound and stable under the dynamic conditions. In order to conserve weight a light motors were used in conjunction with gearboxes. The robot showed it was physically capable of moving but it has problems power issues.

1 Table of contents

2 List of Equations

3 List of Figures, Tables and Pictures

4 List of Symbols

A	3rd order constant for return equation
α	Angular compliment of theta
B	2nd order constant for return equation
C	1st order constant for return equation
d	Center to center distance foot to lower bearing
D	0th order constant for return equation
f	Friction force on ground
F_1	Upper force on Hub
F_2	Lower force on hub
F_{high}	Reaction of upper track
f_x	Forces on leg in x direction
F_x	Forces on body in x direction
f_y	Forces on leg in y direction
F_y	Forces on body in y direction
g	Acceleration of gravity
h	Axel height
i	Current
I	Moment of inertia of leg about axel
J_{xy}	Moment of inertia of leg about centroid
k	Motor torque constant
l	Center to center distance foot to top of leg
M	Mass of cart minus legs in contact with ground
m	Mass of leg
N	Normal force on ground
n_1	Number of gear teeth on gear 1
n_2	Number of gear teeth on gear 2
ω	Angular velocity.
φ	Angle of contact with track.
π	Trigonometric constant.
ψ	Angular displacement, track and bearing center
R	General radius
r	Radius of track
R_{bear}	Radius of bearing
R_{foot}	Radius of center of lower foot during work
R_{high}	Radius of center of high bearing during work
R_{low}	Radius of center of low bearing during work
$R_{rethigh}$	Radius of center of high bearing on return path
R_{retlow}	Radius of center of low bearing on return path
R_{top}	Radius of center of top of leg during work
s	distance from axel to hub slider
t	Time
T	Torque exerted on leg
T_1	Torque on gear 1
T_2	Torque on gear 2
θ	angle of leg
θ_c	Angle of leg when first in contact with ground
θ_{span}	Angular width of gait
v	Velocity of cart
w	width of leg
W	wheelbase of walker
X	Horizontal potion
x_1	first horizontal position of foot
x_2	second horizontal position of foot
x_{span}	linear width of gait
Y	Vertical position
y_{clear}	Clearance height of walker

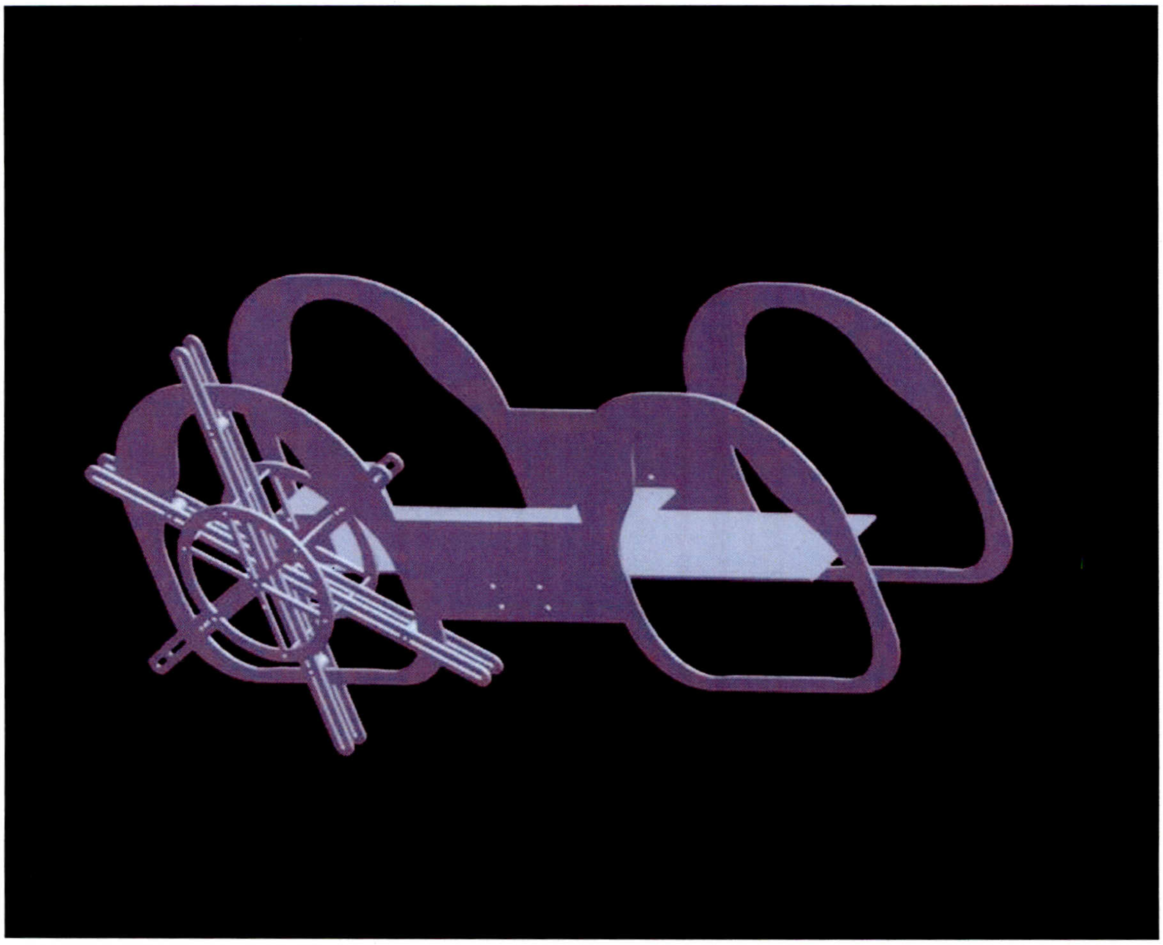
5 Introduction

The Cam driven walker was first introduced in the Master's Thesis of Xiaona Wan, in the Department of Mechanical Engineering of Northern Illinois University.

The principle is that an axel can rotate a slider that is perpendicular to it. The slider holds a leg, which can move freely back and forth but not rotationally. The leg is fixed on a track loop, which allows the leg to rotate freely but not slide back and forth. The combined effect of these two objects causes the lower tip of the leg to move in a strait path. The advantage of this leg over other leg designs is that this leg creates a level motion. Mathematical analysis can create a track with a desired shape for the cam. Structural analysis provided design optimization.[1]

Standard leg designs always create some kind of arc with the foot. The cam-controlled leg does not stop and reverse. This is advantageous over standard leg designs, which must have a return path. This allows all members to work at the same time. This prevents wasted energy from decelerating the leg to reverse its direction.[2] The cam controlled leg is advantageous over the wheel because it can step over obstacles.[3] It also does not leave large tracks where it treads do.[4] One advantage of the walker that is unique to this design is that the rotating legs give it a natural climbing ability over anything that is at the heights of the axel and under certain circumstance the obstacle may be higher. The robot will also be difficult to hang up as its legs provide a motion that clears obstacles. The disadvantage of the robot is the large size of the pods compared to the robot legs. Another disadvantage of the robot, like most leg devises, the motion is not at a constant velocity. This creates a control problem, which will need to be addressed in the future by another project team.

Picture 1



(Walker model with one pod shown.)

6 Project Goals and Tasks

Goal

The project goal is to create a cam based robot capable of self powered movement in a striate line. The Robot should also be able to clear obstacles.

Task listing

The main goal can be broken into individual tasks. The tasks are as follows. (See figure. 1)
Table 1

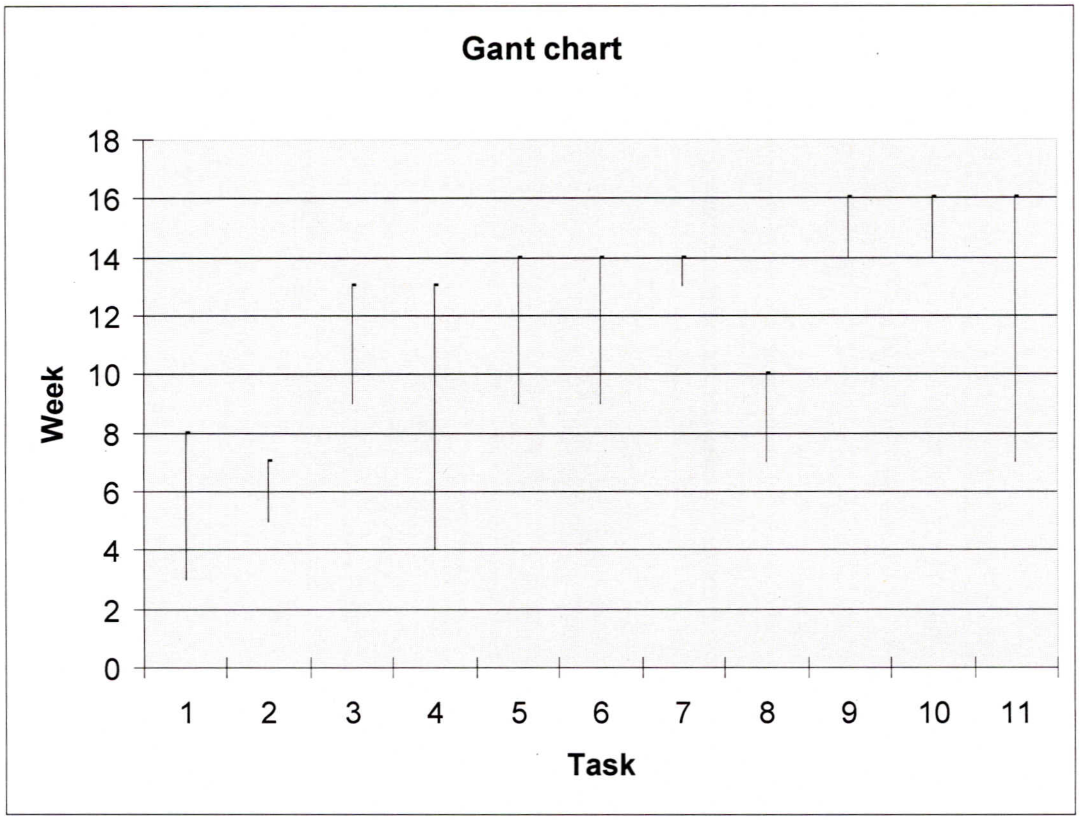
Task 1	Generate curve from theory.
Task 2	Create mathematical model of curve.
Task 3	Finalize part shape and design.
Task 4	Determine materials.
Task 5	Determine forces on walker.
Task 6	Analyze strength of materials.
Task 7	Cut the basic parts.
Task 9	Determine power source.
Task 10	Assemble the walker.
Task 11	Test the walker.
Task 12	Formal Documentation.

(timetable planning)

Timetable Planning.

The timeline of the project consisted of completely several major tasks at once. The timeline started the third week of school with the confirming the original equations. Which was further investigated until the eighth week. Curve design started the fifth week and ended the seventh week. Part finalization started on the ninth week and ended the thirteenth week. Material selection was started on the fourth week and ended on the seventh week Force analysis started on the ninth week and ended on the fourteenth week. Strength analysis started on the ninth week and ended on the fourteenth week. Parts were constructed on the thirteenth and the fourteenth week. The power source analysis started on the seventh week and ended on the tenth week. Part assembly started on the fourteenth week and ended on the sixteenth week. Walker testing started on the fourteenth week and ended on the sixteenth week. Documentation started on the seventh week and ended on the sixteenth week.

Figure 1



(Gant Chart)

8 Walker Design.

Theory:

The basic theory of the cam-controlled walker is mathematical. The principle design requirements are dictated by the relationship of polar motion. (Eq.1,2) Path of the leg tip can be defined as a horizontal strait line in polar coordinates with a height of 13.65cm. The desired path of the slider is taken by subtracting distances form the footpath. (Eq.4,5)

$Y = -h$ eq.1

$R\sin\vartheta = -h$ eq.2

$$R_{foot} = \frac{-h}{\sin\theta} \quad \text{eq.3}$$

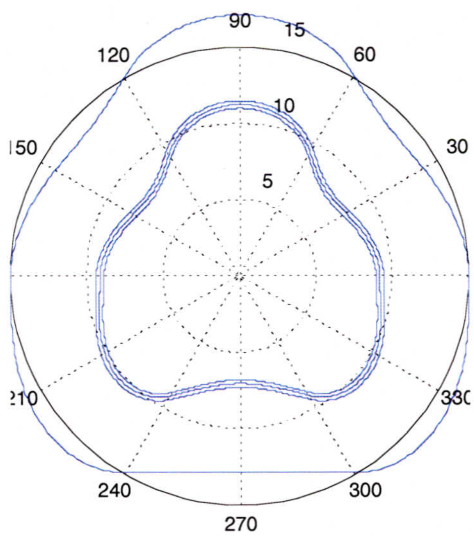
$$R_{low} = \frac{-h}{\sin\theta} + d \quad \text{eq.4}$$

$$R_{high} = \frac{-h}{\sin\theta} + l - d \quad \text{eq.5}$$

$$R_{top} = \frac{-h}{\sin\theta} + l \quad \text{eq.6}$$

$$\frac{dR_{foot}}{d\theta} = \frac{dR_{low}}{d\theta} = \frac{dR_{up}}{d\theta} = \frac{dR_{top}}{d\theta} = \frac{h * \cos\theta}{\sin^2\theta} \quad \text{eq.7}$$

Figure 2



(Foot, tack, bearing, and clearance paths.)

The limiting factor of the geometry is the force angle. This is the angle relative to the current radius of the track that the force from the wall is applying. The ideal force path passes strait through the axel and creates no retarding torque. The worst situation is when the force is perpendicular to the member and 100% of the normal force translates to retarding torque. The design specification was set that the majority of the normal force would be parallel to the member. This limit is when the angle is less than 45 degrees. The angle can be found by a relation of change in radius to change in angular position.(Eq.8,9)

Other design constraints of the curve were an attempt to maximize the gait span, and clearance height. The angular span on the ground and the hip height of the walker are both positively related to the width of the gait span.(eq.10) The clearance height is directly related to the distance from the foot to the cam tack.(eq.11) The limitations lie in that as gait angle, hip height, and distance from the foot to the cam slider and negatively related to the force angle.

$$\tan\psi = \frac{\frac{dR}{d\theta}}{R} \quad \text{eq.8}$$

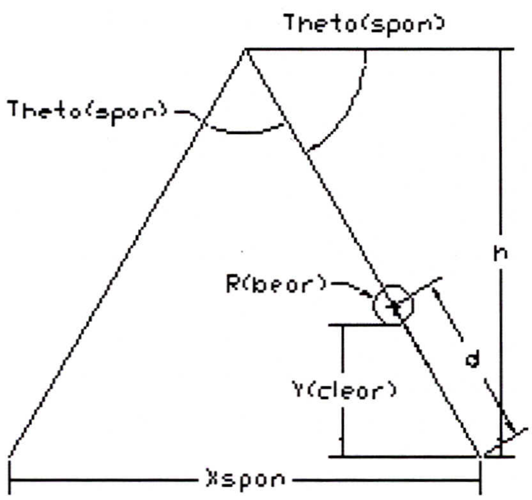
$$\psi = a\tan\frac{\frac{dR}{d\theta}}{R} \quad \text{eq.9}$$

$$x_{span} = 2 * h * \tan\frac{\theta_{span}}{2} \quad \text{eq.10}$$

$$y_{clear} < d * \cos\frac{\theta_c}{2} - R_{bear} \quad \text{eq.11}$$

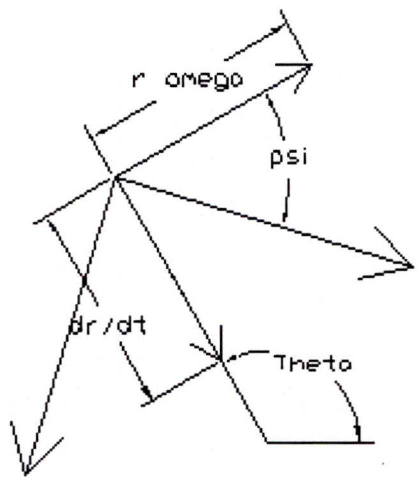
Figure 3

Span and clearance



(Span and clearance height.)

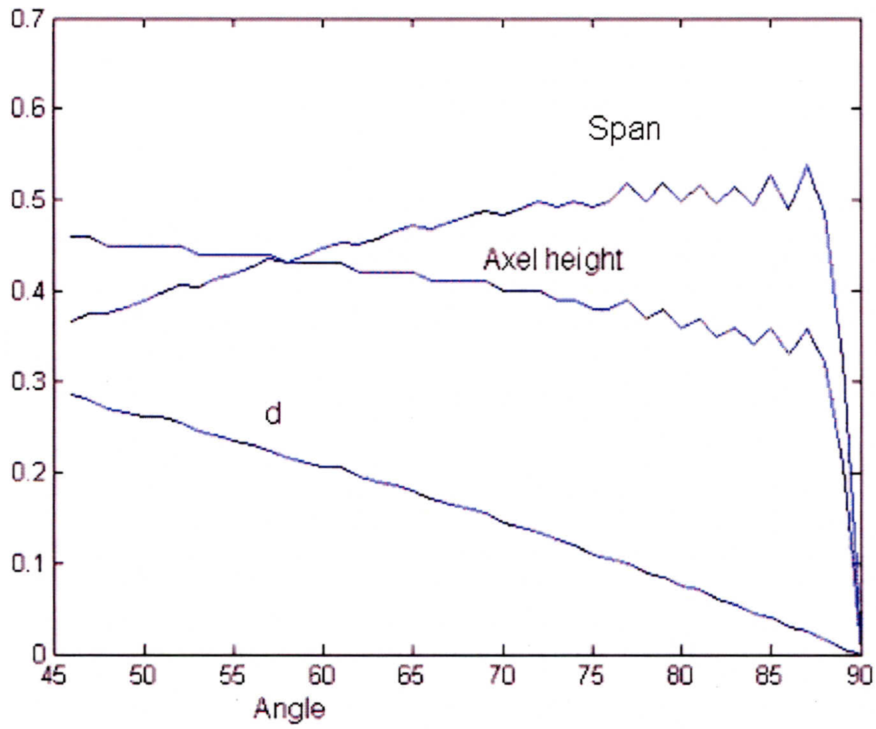
Figure 4



(Bearing velocities and force.)

An iterative approach for optimizing the specifications was used. A fine increment of distances between foot and slider, height and angle were utilized.(See Appendix B "Angles") The maximum distance for each angle and its corresponding height was determined. The result was a decision to go with a 60-degree span on the ground. The advantage of the 60-degree angle is that it evenly divides the rotation into 6 segments parts. 60 also had the maximum clearance height with an acceptable relative reduction of the gait span. Although the original design called for a 90-degree angle span the analysis showed that in order to get an acceptable force angle the clearance would be immeasurably small. (See fig. 5) The maximum distances for the 60 degree were chosen to be h=.43L and d=.195L(See fig. 6)

Figure 5



(Angular span vs. d/l, h/l, and x_{gait}/l)

Because the part of the track that the leg is in contact with while it does work only sweeps 120 degrees of a 360-degree rotation a return track is required. The easiest method of finding a curve with the desired features is a polynomial spine.(eq.12,13) The limiting factors were that the distance of the return track to the axel and the angle of the track relative to the member must be equal to that of the work track when they meet.(eq 16,17) The other limiting factor is that when the leg is horizontal the path must be vertical and the leg must be centered relative to the axel.(eq.14,15) The result is the following analysis.

$$R_{retlow} = A\vartheta^3 + B\vartheta^2 + C\vartheta + D \quad \text{eq.12}$$

$$\frac{dR_{retlow}}{d\theta} = 3A\vartheta^2 + 2B\vartheta + C \quad \text{eq.13}$$

$$R_{retlow}(0) = \frac{l}{2} - d \quad \text{eq.14}$$

$$\frac{dR_{return}(0)}{d\theta} = 0 \quad \text{eq.15}$$

$$\frac{dR_{return}(\theta_c)}{d\theta} = \frac{dR_{low}(\theta_c)}{d\theta_c} \quad \text{eq.16}$$

$$R_{retlow}(\theta_c) = R_{low}(\theta_c) \quad \text{eq.17}$$

These equations were analyzed using the algebraic substitution.(see Appendix B: “Paths” and “xy”)

The upper part of the return track was found by subtracting l-2d from the resulting lower paths.(eq.18)

$$R_{rethigh} = R_{retlwo} - l + 2d \quad \text{eq.18}$$

Table 2

A	B	C	D
-7.6605	64.2716	-177.0123	150.1384

(Return path coefficients)

Although in working applications the there are many other maters which must be considered, which include continuity of the second and third derivative of the radius to the angle, these analyses will not affect the design or performance of this prototype. Wan covered them accurately and in detail in his thesis. An additional analysis would be redundant and not applicable.

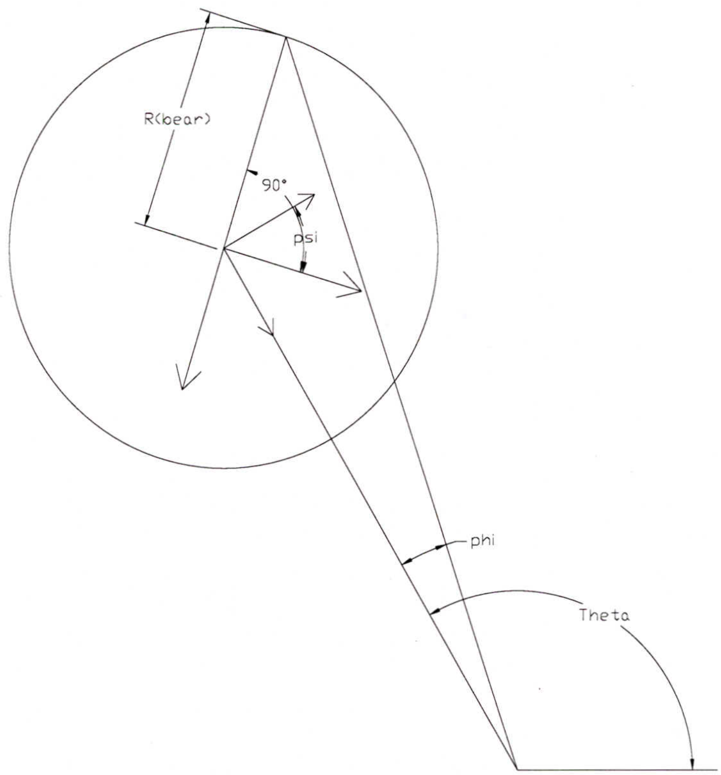
The actual shape of the track that the bearings run on is not the same path traced by theory. The reason is that the track must be offset by the radius of the bearing in the direction perpendicular to the path of the track.(Eq 19-20)(See fig. 6)

$$r = \sqrt{R_{bear}{}^{2} + R^{2} - 2R * R_{bear} * \cos(180 - \psi)} \qquad \text{eq.19}$$

$$\frac{\sin(180 - \psi)}{|r|} = \frac{\sin(\phi - \theta)}{R_{bear}} \qquad \text{eq.20}$$

$$\phi = a\sin\left(\frac{\sin(180 - \psi) + R_{bear}}{|r|}\right) + \theta \qquad \text{eq.21}$$

Figure 6

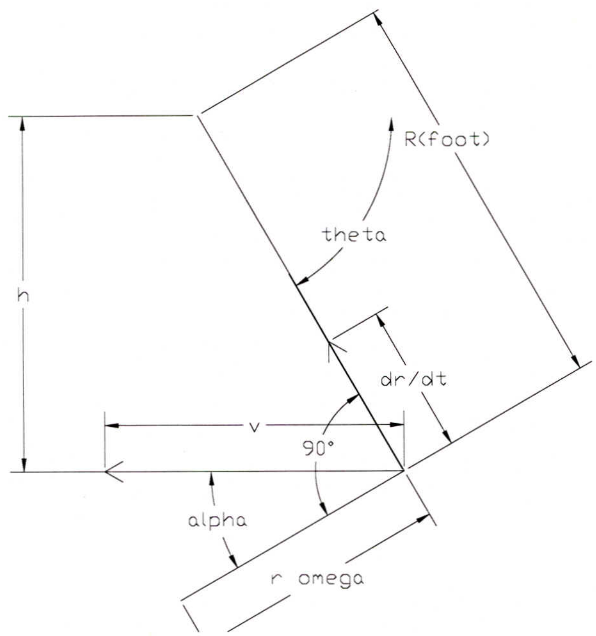


(Track position relative to bearing and axel position.)

Motion

The physical motion of the walker is directly related to the physical motion of the foot. The speed of the walker is identical to the motion of the foot. While there is a factor that must be accounted for due to the rotation of the foot along the circular path of its rounded shape, the velocity effect is constant and will be neglected from the following discussion as it only affects overall speed. Also, depending on the foot design the velocity adjustment could be non-existent. The following discussion is a parametric examination of the foot speed, of the walker. Note that the height never changes in the work position.(eq.28) The velocity does change.(eq.35) (See Fig. 7)

Figure 7



(Foot velocities)

$$R_{foot} = \frac{-h}{\sin\theta} \quad \text{eq.22}$$

$$R_{foot} = \sqrt{x^2 + y^2} \quad \text{eq.23}$$

$$\frac{dR_{foot}}{dt} = \frac{-\tfrac{1}{2} * (2x * \frac{dx}{dt} + 2y * \frac{dy}{dt})}{\sqrt{x^2 + y^2}} \quad \text{eq.24}$$

$$\frac{dR_{foot}}{dt} = \frac{h * \cos\theta}{\sin^2\theta}\frac{d\theta}{dt} \quad \text{eq.25}$$

$$\frac{d\theta}{dt} = \omega \quad \text{eq.26}$$

$$\frac{dx}{dt} = v \quad \text{eq.27}$$

$$\frac{dy}{dt} = 0 \quad \text{eq.28}$$

$$\frac{h * \cos\theta}{\sin^2\theta}\omega = \frac{-x * v}{\sqrt{x^2 + y^2}} \quad \text{eq.29}$$

$$\cos\theta = x / R_{foot} \quad \text{eq.30}$$

$$\sin\theta = y / R_{foot} \quad \text{eq.31}$$

$$\frac{-h * x / R_{foot}}{(y / R_{foot})^2}\omega = \frac{x * v}{R_{foot}} \quad \text{eq.32}$$

$$v = \frac{-hR_{foot}{}^2\omega}{y^2} \quad \text{eq.33}$$

$$v = \frac{-R_{foot}{}^2\omega}{h} \quad \text{eq.34}$$

$$v = \frac{-\omega}{h}\left(\frac{-h}{\sin\theta}\right)^2 \quad \text{eq.35}$$

This shows that velocity of the foot of the walker is dependent on axel height, angular velocity and the angle of the leg. Axel height and angular velocity are constant. Angle, however, is not constant. As a result velocity is not constant.

This is contradictory to a claim made by Wan in the Master's Thesis, which states that for a constant angular input there is a constant velocity output.[5] This argument is based on the following analysis. (See Fig. 7)

$$\frac{dy}{dt} = -\omega R_{foot}\sin\theta \quad \text{eq.36}$$

$$v = -\omega R_{foot}\cos\theta \quad \text{eq.37}$$

$v = -\omega h$ eq.38

Since angular velocity and height are constant velocity would need to be constant. Wan omitted the component of changing length, which results, when incorporated in the analysis, in the following situation.[6] Note that equations 39 and 41 are equations 36 and 37 respectively with additional terms added for change in radius. (See Fig. 7)

$$\frac{dy}{dt} = \frac{dR_{foot}}{dt}\sin\alpha - \omega R_{foot}\sin\theta$$ eq.39

$$\frac{dR_{foot}}{dt} = \frac{\omega R_{foot}\sin\theta}{\sin\alpha}$$ eq.40

$$v = \omega R_{foot}\cos\theta + \frac{dR_{foot}}{dt}\cos\alpha$$ eq.41

$$v = \omega R_{foot}\cos\theta + \frac{\omega R_{foot}\cos\alpha\sin\theta}{\sin\alpha}$$ eq.42

$\sin\alpha = \cos\theta$ eq.43

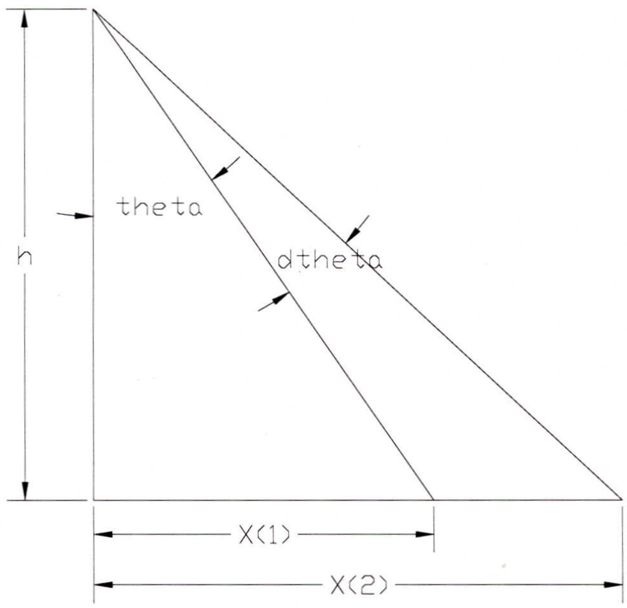
$$v = \omega h + \frac{\omega R_{foot}\cos\alpha\sin\theta}{\cos\theta}$$ eq.43

$v = \omega h + \omega R_{foot}\sin\theta\tan\theta$ eq.44

$v = \omega h + \omega h\tan\theta$ eq.45

This verifies that the velocity of the foot depends upon the angle, axel height and angular velocity. To reconfirm this as it contradicts statements of others this separate analysis was conducted using the following trigonometric relations.(See fig 8) The principle is that in any even period of time the angular displacement will be constant. For an equal displacement of angle an equal displacement of distance will not exist because the angle also effects displacement.(eq.50)

Figure 8



(Change in foot position relative to angle)

$\tan\theta = x_1 / h$ eq.46

$\tan(\theta + d\theta) = x_2 / h$ eq.47

$x_1 = h * \tan\theta$ eq.48

$x_2 = h * \tan(\theta + d\theta)$ eq.49

$dx = x_2 - x_1 = h(\tan(\theta + d\theta) - \tan\theta)$ eq.50

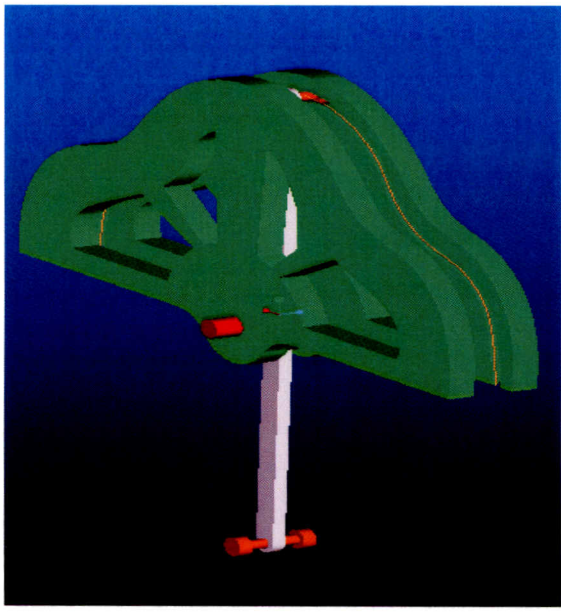
This displays that the displacement of the leg is a result of both angle and angular displacement.

Although the effect on a model of this scale is minimal there the inconsistent velocity may become a very important factor in larger pieces of equipment that are moving much more massive loads.

Specifications

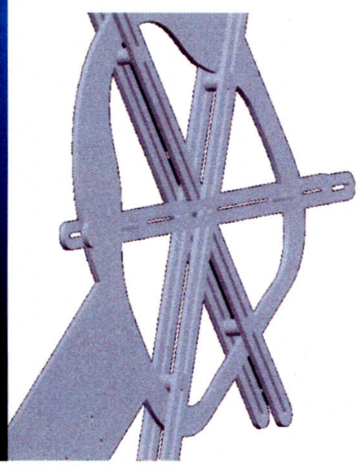
The original thesis wanted a singular member with a two tracks on each side of it. Each track would have both an inner and outer running surface.(see Picture 2)[7] For this project the track design was modified to allow for a dual member. The member consists two legs that are connected with two cross pins.(See Pic. 3,4,5) The pins will have the bearings mounted on them. The legs will be on either side of a singular track with only an outer contact surface. This allows for a much easier to construct walking pod.

Picture 2



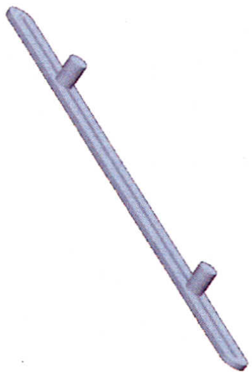
(Original track arrangement)[8]

Picture 3



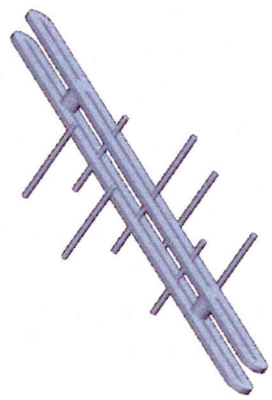
(New track arrangement)

Picture 4



(Half leg with spacers)

Picture 5



(Full leg with torque pins and axel)

The length of the leg was decided to be 30 cm. The shape of the actual track curve was decided determined after the bearing diameter was fixed to 1 cm. The material to make the legs was determined to be acrylic because of its lighter weight. Analysis shows a 45% reduction in weight of the members and hubs compared to that of steel. The width of the leg was set to 1 cm and rounded on the end to allow for a smooth step. To prevent excessive deflection the width was increased to 1.5 cm(See Table 3)

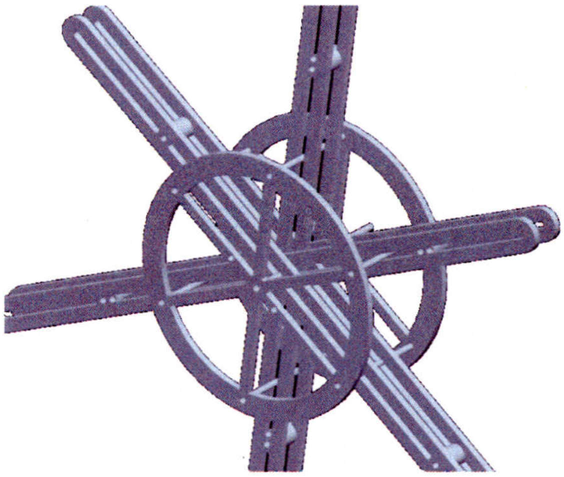
Table3

Component	Original design	Final design
l	30cm	30cm
s	5.55cm	5.55cm
d	5.85cm	5.85cm
w	1cm	1.5cm
m	.056kg	.015kg
R_{bear}	.5cm	.5cm

(Leg specifications)

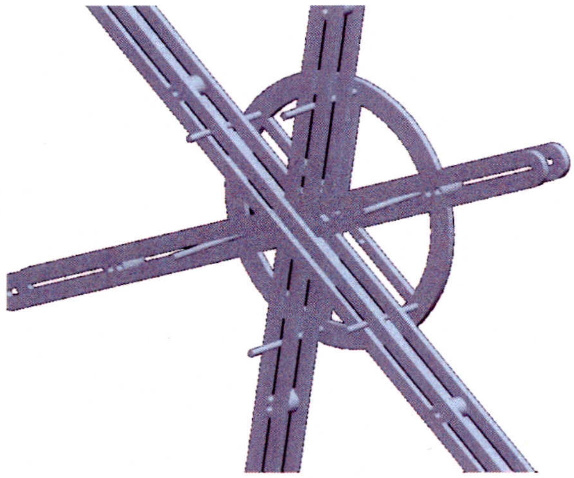
The hub was decided to be two wagon like wheels with rods connecting them.(see Pic.6) The rods would transmit the torque to the members.(see Pic.7) The hubs must be smaller than the minimum clearance of the bearing on the members as that would result in a collision. The hubs will have radius of 5.55 cm

Picture 6



(Hub and legs)

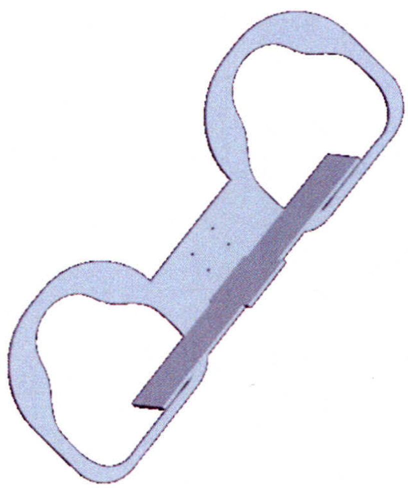
Picture 7



(Hub and legs, half hub removed)

The wells will be plastic. They will be flat sheets with the shape of the track cut out. The two tracks will be connected to each other with a central span. The central span will connect to base. . The following specifications were made for the cart. The lengths were determined as previously stated. The wheelbase is determined to be 39 cm. The maximum mass is set at most 2 kg.

Picture 8



(Base and wells)

Table 4

W	39 cm
M	1.944kg
Mass of base	.144kg
Mass of well	.175kg
Mass of hub	.018kg

(Specifications of body, theoretical)

Analysis.

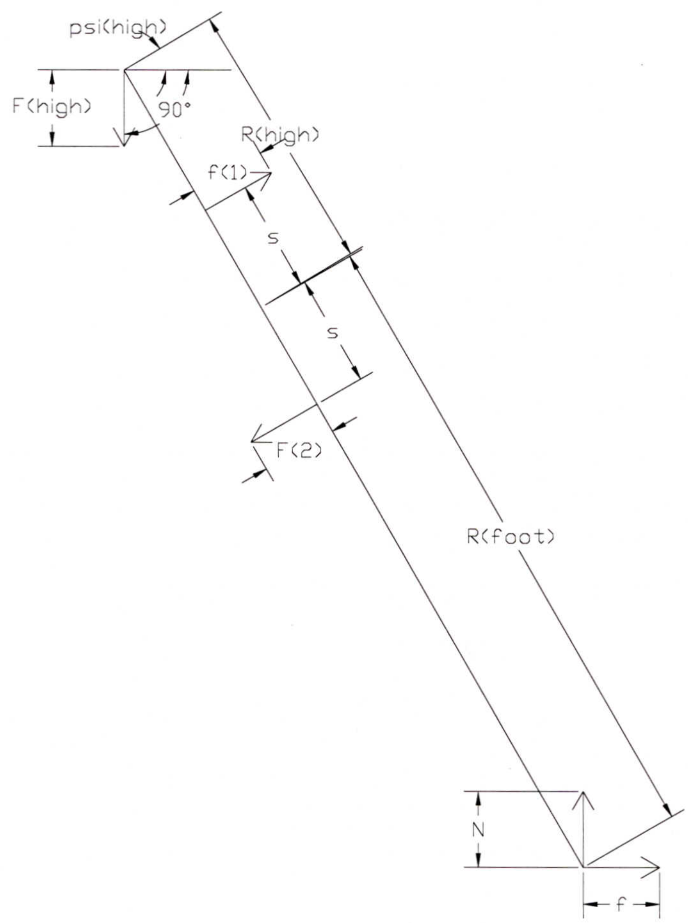
The forces in the legs must be determined in order to determine structural integrity, and torque requirements.

The forces must be determined with respect to critical positions of the legs. The critical points with respect to when the leg is in a working stroke. The most important angles are when the leg is just making or leaving contact with the ground. The other critical position is when the leg is vertical. The forces must be determined all points which the leg contacts something else.

The angles of the forces are determined by the geometry of the track. The following analysis of the forces determines these relationships. Using a Jacobean method of solving simultaneous equations the forces can be determined.

The force balances are as follows.(See fig. 9)

Figure 9



(Force diagram on leg)

$$\Sigma f_x = F_2 \sin\theta - F_1 \sin\theta + F_{high} \cos\psi_{high} + f \quad \text{eq.51}$$

$$\Sigma f_y = F_2 \cos\theta - F_1 \cos\theta + F_{high} \sin\psi_{high} + N - mg \quad \text{eq.52}$$

$$\Sigma F_x = -F_2 \sin\theta + F_1 \sin\theta - F_{high} \cos\psi_{high} \quad \text{eq.53}$$

$$\Sigma F_y = -F_2 \cos\theta + F_1 \cos\theta - F_{high} R_{high} \sin(\psi_{high}) + Mg/2 \quad \text{eq.54}$$

$$\Sigma T = -F_2 s - F_1 s + F_{high}\sin(\theta - \psi_{high}) + NR_{foot}\cos\theta + fR_{foot}\sin\theta \quad \text{eq.55}$$

The acceleration components are as follows.

$$\Sigma F_y = 0 \quad \text{eq.56}$$

$$\Sigma F_x = M\frac{d^2x}{dt^2} = M\frac{d\left(\frac{-\omega}{h}\left(\frac{-h}{\sin\theta}\right)^2\right)}{dt} \quad \text{eq.57}$$

$$\Sigma F_x = \frac{2M\varpi^2 h\cos\theta}{\sin^2\theta} \quad \text{eq.58}$$

$$\Sigma T = \frac{dI\omega}{dt} \quad \text{eq.59}$$

$$I = j_{xy} + m(R_{top} - l/2)^2 = J_{xy} + m\left(\frac{-h}{\sin\theta} + l - l/2\right)^2 \quad \text{eq.60}$$

$$\Sigma T = \frac{2m\cos\theta}{\sin^2\theta}\left(\frac{-h}{\sin\theta} + l - l/2\right) \quad \text{eq.61}$$

$$\Sigma f_x = m\frac{d^2x}{dt^2} = m\frac{d\left(\frac{-\omega}{h}\left(\frac{h}{\sin\theta}\right)^2 + \frac{h\omega * \cos^2\theta}{\sin^2\theta} + \omega\sin\theta\left(\frac{-h}{\sin\theta} + l - l/2\right) + \omega w/2\right)}{dt} \quad \text{eq.62}$$

$$\Sigma f_x = m\left(\frac{2\omega^2 h\cos\theta}{\sin^2\theta} + 2h\omega^2\left(\tan^3\theta + \tan\theta\right) + \omega^2\left(\cos\theta\left(\frac{-h}{\sin\theta} + l - l/2\right) - \frac{h\cos\theta}{\sin\theta}\right)\right) \quad \text{eq.63}$$

$$\Sigma f_y = m\frac{d^2y}{dt^2} = m\frac{d\left(\frac{h\omega * \cos\theta}{\sin\theta} + \omega\cos\theta\left(\frac{-h}{\sin\theta} + l - l/2\right)\right)}{dt} \quad \text{eq.64}$$

$$\Sigma f_y = m\left(\frac{-h\omega^2}{\sin^2\theta} + \omega^2\left(-\sin\theta\left(\frac{-h}{\sin\theta} + l - l/2\right) + \tan^2\theta * h\right)\right) \quad \text{eq.65}$$

Using a Jacobean method of solving of the problems yields the following results in table 4.

Please note that there was no force determined for the lower track contact. The reason for this is that the lower track should not need to apply any force as it is not supporting any weight. It only exists to prevent the legs from becoming dislodged. If the more complex dual track is introduced such as was originally proposed by Wan then the contact forces are not negligible.[9] In order to account for this, another equation must be introduced one possible equation is the moment analysis of the entire cart. Also frictional forces were assumer negligible for anyplace but the floor. Note that the forces are at maximum when the leg is at the ends of the gait. (See table 5)

This cart however can experience force even when the leg is not in working position. The leg can extend and contact an obstacle when it is not in contact with the ground. The forces involved in this operation are directly proportional to the moment induced by the force. Since moments are maximum when the leg is fully extended the forces will be maximum when the leg is fully extended. The moments would have to balance with the weight of the cart. When fully extended the leg is only in contact with the obstacle and the bearings that transmit torque from the axel to the leg. The following forces relation is experienced.

$$N = Mg/(W + l/2) * l/2 \quad \text{eq.66}$$

$$F_1 = \frac{N(l/2 - s)}{2s} \quad \text{eq.67}$$

$$F_2 = \frac{N(l/2 + s)}{2s} \quad \text{eq.68}$$

Table 5

Angle	f	N	T	F_1	F_2	F_{high}
90	5.926N	19.63N	-.6828N-M	-7.6206N	.5773N	19.4434N
60	10.68N	19.6366N	-.3909N-m	-7.6206N	.5773N	15.74N
0	0N	7.034N	-1.1718N-m	13.022N	5.988N	0N

(Force analysis of legs)

Note that the torque requirements are at maximum when the walker is attempting to lift itself.

Power Concerns

In order for the walker to be able to adequately climb any obstacle it requires a torque of 1.2 n-m or 12232g-cm at the gearbox. The gearboxes themselves are rated only at 2020g-cm. However this is not because of a fault of the motor. The ratio of input to output torque is a direct proportion to the gear ratio. The gearbox has 4 speeds, two of which are clutched two of which are not clutched. The correlation of gear ratios is as follows.

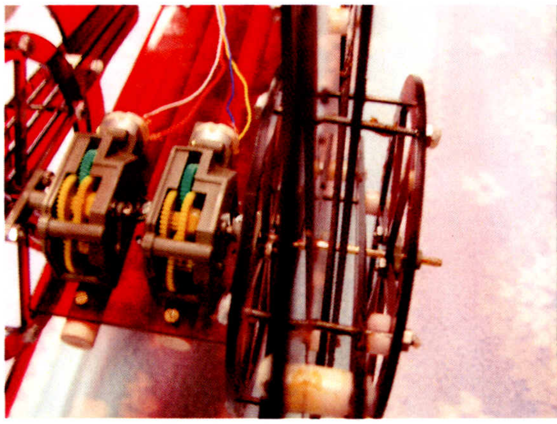
$$\frac{n_1}{n_2} = \frac{T_1}{T_2} \quad \text{eq.69}$$

This correlation can be chained to multiply the factor.[10]

The reasoning behind a clutch is to prevent material failure. The following measures were taken to allow for a gear box that would not be clutched but also would not fail under load. The weights of the parts needed to be minimized. As such, emphasis was placed on a lighter parts and a simplified design that would reduce weight. The material was changed from steel to acrylic. Also the recommended gearbox setup was deviated from in order to transmit torque the following ways. The clutches were removed from the gearboxes to allow for a higher torque ratio of 5189g-cm. which when doubled it is 10,378g-cm, which is not adequate to lift the walker at the intended mass.

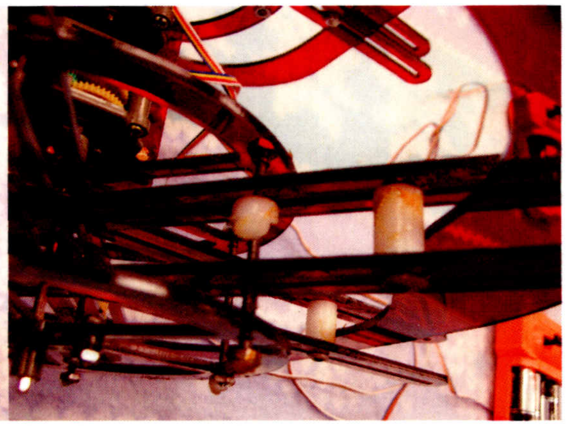
In order to reduce weight bearings were not used. Instead a plastic sleeve was placed over the pins of the legs to fill in the gap.(See Pic. 9)

Picture 9



(Gearboxes)

Picture 10



(Plastic sleeves, and retaining clips)

One method of increasing torque is by increasing voltage to the motors.. This will in turn increase the current flowing through them. The current flowing through them is directly proportional to the torque produced by the motors(See eq.70)

$T = ki$ eq. 70[11]

Stress analysis

Stress is the force of a load distributed over the cross sectional area of the material. Von Meisis method of stress analysis was preformed because it is considered conservative and therefore has the highest possibility of creating the part that is least likely to fail.[12] The rating of strength of a material is the factor of safety. It is the ratio of the maximum stress a martial will experience to the maximum it can experience without failing.[13]

Stress analysis is essential for failure analysis in a support device. Failure analysis was first preformed on a solid leg with holes for attaching bearings. This resulted in a maximum stress, which is far less than the maximum stress of 10000 psi.[14] For the concerns of weight a center channel was removed from the leg. One advantage of the center channel is that during the times when the leg is not being loaded the axel running through the channel work to hold the leg in place. This reduces the bearings in the slider by half. This is a significant reduction in weight. The final stresses in the leg were determined to be 2018psi which results in a factor of safety of 5

Another part on which stress analysis was preformed was the torque transmitter from the axel to the legs. Originally a star shaped patter was intended to be used. However, it was considered strength improvement to connect all the contact points in a wagon wheel pattern. This transmits stress in one part to all radial members as opposed to just one. The current factor of safety is 3.7. The stress analysis in the axils resulted in a maximum stress of 3,428psi. The stress analysis was taken when the member was horizontal because the forces were calculated to be maximum. The stress analysis in the wells resulted in a factor of safety of 30 with a maximum stress of 329pis. The stress analysis was preformed at horizontal and when the leg first contacts the ground. These comprise the limits of the forces.(See Table 6)

Table 6

Part	Maximum stress	Maximum displacement	Factor of safety.
Hub	3,428 psi	.039 in	3.7
Leg (new)	2018 psi	.17 in	5
Leg (old)	5504 psi	.64 in	1.8
Wells	1074 psi	.02 in	9.3
Body	3304 psi	1.6 in	3.1

(Stress and displacement of manufactured parts)

9: Decision matrix

The first decision is the determination of materials. The important factors were weight machineability and strength. Only plastic and steel were considered.

Table 7

Criterion		steel	Acrylic
Weight	20 -		3
strength	20 -		-2
machineability	20 -		2
Flexibility	10 -		-1
Thickness	10 -		1
	total +	0	6
	total -	0	-3
	overall total	0	3
	Weighted total	0	60

(Decision matrix material)

Another important factor to be determined was the choice of power sources for the walker. There were three choices, stepper motors, direct dc motor, dc motor with a gearbox. The important criteria were cost, speed, torque and weight.

Table 8

Criterion		Gear boxes	DC	Stepper
weight	20 -		-2	-2
speed	10 -		-2	1
Torque	40 -		0	-2
cost	30 -		0	-2
	total +	0	0	1
	total -	0	-4	-6
	overall total	0	-4	-5
	Weighted total	0	-60	-170

(Decision Matrix Power Supply)

The third factor to be determined was the width of the leg. A thinner leg was desired for weight but there were also the matters of flexibility and strength to consider. The comparison was between a 1cm leg a 1.5 cm leg.

Table 9

Criterion		1 cm	1.5 cm
Weight	10	-	-1
Strength	60	-	2
Flexibility	40	-	3
	total +	0	5
	total -	0	-1
	overall total	0	4
	Weighted total	0	240

(Decision matrix leg width)

A more crucial decision was made when deciding the orientation of the tracks. The original design had the rollers bracketed on both the inside and outside. An alternative design was to have the rollers only bound on the outside. These designs were compared on the basis of cost, manufacturability stability and strength.

Table 10

Criterion		Two Boundaries	One Boundary
Cost	10	-	1
Manufacturability.	40	-	3
Stability	25	-	-2
Strength	25	-	1
	total +	0	5
	total -	0	-2
	overall total	0	3
	Weighted total	0	25

(Decision matrix number of tracks)

Another engineering decision to be made was the hub design. There were several design possibilities. The first included that each member get its own sleeve with rollers on the end. The next design it that each member gets a sleeve with no rollers. A final design suggests that the rod pass through the member that can slide axially in the member. The possibilities were examined on the basis of manufacturability. size, weight space and friction.

Table 11

Criterion		Weight	Rollers	slider	rod
weight		10 -		2	2
size		20 -		1	3
manufacturability		30 -		1	3
cost		30 -		2	3
friction		10		-1	-1
	total +		0	6	11
	total -		0	-1	-1
	overall total		0	5	10
	Weighted total		0	90	250

(Decision matrix Hub design)

The final decision was made about the choice of bearings. The choices were either purchased bearings or manufactures plastic sleeves. The criteria were cost, weight, size, and friction.

Table 12

Criterion		Weight	Bearing	Sleeve
weight		30 -		2
size		30 -		1
cost		10 -		2
friction		30		-1
	total +		0	5
	total -		0	-1
	overall total		0	4
	Weighted total		0	80

(Decision matrix bearings)

10 Parts and Bill of Materials.

The walker is broken into two main parts: the chasse and the pods. The chasse consists of wells and the body. The pods consist of the power source legs and hubs, which can be broken down into subsequent parts as follows

Walker
- I Chasse
    - A Wells
    - B Board
    - C Purchased Brackets
    - D Purchased Screws
    - E Bracing
        - i cut dowel rod
        - ii Purchased screws
- II Pods
    - A Legs
        - i plastic member
        - ii plastic spacer
        - iii purchased screw
        - iv purchased nut
    - B Hubs
        - i plastic hub
        - ii purchased threaded rod
        - iii purchased nuts
    - C power source
        - i purchased motor
        - ii purchased gearbox
        - iii purchased control box
        - iv purchased screws
        - v purchased nuts

Table 13

Part	Description	Quantity
Acrylic sheet	1/8 in acrylic sheet*	12 ft^2
1/2 in dowel	1/2 inch wooden dowel rod*	36 in
Durland rod	10ftx .5 in durland rod*	10 ft
Wells	24 inch acrylic walking wells	2
Body	18 inch acrylic main body	1
Hubs	Acrylic Torque transmission hubs	8
Legs	31.5 cm acrylic legs	24
Motors	4 speed tamiya motor and gear box	4
Control Box	two channel tamiya control box	2
Brackets	1.5 inch 90 deg steel brackets	4
1/8x1/2in screw	1/8x 1/2 Philips pan head screws	8
1/8 in nut	1/8 in nut	8
18 in dowel rod	1/2 x 18 inch wooden dowel rod	2
#4 screw	flat head wood screws	6
plastic spacer	1.5 cmx1 cm dia plastic spacer	24
#4 nuts	#4-40 nuts	98
#4x1/4 screw	4-40 X 1/4 inch cap screw	16
#4x7/8 screw	4-40 X 7/8 inch cap screw	24
#4x 2 in rod	4-40 X 2inch threaded rod	24
	* used as raw material	

(Bill of material)

11 Budget

No actual budget was set for the project however the project would be considered better off if personal expenses were below $100. The plastic sheet was provided for by the College of engineering and engineering technology. The durland Rod and some fasteners were provided by family members. With this assistance the project managed to stay on a very low budget. The following is an expenditures breakdown.

Table 14

Part	Cost per unit	total cost
Provided parts		
Plastic rod	$10	$10
Plastic sheet	$8/ft^2	$96
Threaded rod	$0.20	$10
Other fasteners		$10
Total provided		$126
Purchased parts		
Motor	$11	$44
Control boxes	$12	$24
Dowel Rod	$1.50	$1.50
Epoxy	$5	$10
Brackets	$5	$5
Batteries	$5	$5
Total purchased		$90
Total Cost		$216

(Budget)

12 House of Quality

One important tool for analyzing a design is the house of quality. The house of quality is used to compare the validity of the walker to other comparable movement devices. The devices that are being compared are the cam driven walker, and oscillatory walker, a wheel driven device and a track driven device. All values are given with respect to the dimensions of the device. The following descriptions are used. Speed over terrain is how quickly can a walker cross terrain. Climb angle is how steep of a grade it can climb. Climb height is high of an object can it scale in a singular incident. Angle of tip is how far one can tip it before it topples. Turn radius is self-explanatory. No data was available for walking devices. No test was preformed for the new design. Soil disturbance is how much soil the device will turn up in for distance walked. No comparable data was available. No test was preformed for the new design. Roughness of terrain is what variance in the ground height can the walker handle. Energy of movement was how much energy does it take to move the device a certain distance. No data was available and no test was preformed.

Figure 14

	Speed over Terrain	Climb Angle	Climb Height	Angle of tip	Turn radius	Soil disturbed	Roughness of terrain	Energy for movement
Speed over Terrain								
Climb Angle	3							
Climb Height	3	9						
Angle of tip	3	9	9					
Turn radius	-1			-1				
Soil disturbed	-1							
Roughness of terrain	9	3	3	3		3		
Energy for movement						3	9	

Weight	Turbine engine	Speed over Terrain	Climb Angle	Climb height	Angle of tip	Turn radius	Soil disturbed	roughness of terrain	Energy for movement	Cam Walker	Oscillatory walker	Wheel	Tread
	Direction of improvements	More	More	More	More	Less	Less	More	Less				
Value	units	M/s	Deg.	M	Deg	M	kg/m	M	J/(m kg)				
25	Terrain crossing	Strong	med	Strong	Med	Weak		Strong		5	5	2	5
20	Climbing ability		Strong	Strong	Med			Med		5	2	2	4
15	Speed	Strong	Med	Med					Med	2	2	5	3
15	Stability		Med		Strong	Weak		Strong		4	3	5	5
10	tight cornering					Strong		Weak		2	2	3	4
5	Power efficiency				Med				Strong	4	3	5	4

	Speed over Terrain	Climb Angle	Climb height	Angle of tip	Turn radius	Soil disturbed	roughness of terrain	Energy for movement
Cam Walker	2	30	h	40	X	low	0.13h	low
Oscillatory walker	2	30	.3h	35	X	low	.3h	med
Wheel	20	30	.1h	45	1.5W	med	.1h	low
Treads	2	50	h	60	0	High	h	med
Target Disgusted	0.5W/sec	10	.2h	30	3W	Unknown	.1h	0
Target Delighted	5W/sec	45	h	60	0	0	1h	Unknown

House of Quality

13 Manufacturing

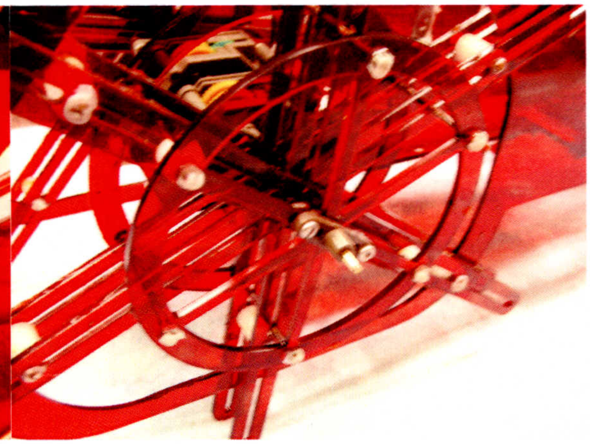
The Details of manufacturing are as follows. The wheel wells the legs hubs and body were all manufactured out of 1/8 inch thick acrylic. The parts were cut with the College of engineering and engineering technologies laser cuter. The spacers which took the place of bearings were made of a _ inch diameter plastic rod. The sliders were milled to specifications using a lathe. All other parts were fastened with screws and nuts.

One interesting outcome of the manufacturing was the selection of an adhesive for the securing of screws and filling in gaps. Several adhesives were available for selection. One was an industrial screw adhesive, such as Loctite brand. These were not considered because of the cost and the permanence of the bond. Epoxies were not considered because they were permanent and very brittle. For the purposes of a prototype a flexible, easily applicable and removable adhesive was required. The solution was hot craft glue. The glue could be easily applied between gawps to act as a filler.(See Pic. 12) It could also be used to secure nuts to screws, but was fragile enough were it could be easily removed if the nut needed to be removed.(See Pic. 13) Hardware epoxy was employed for model repairs. The repairs were facilitated by applying a scrap piece of plastic as a bracing and using it to sandwich he broken joint. Epoxy was employed as an adhesive.(see Pic. 14)

Picture 11

(Hot glue on screws)

Picture 12



(90 degree brackets with hot glue filler)

Picture 13

(Repair bracing)

Picture14

(Dowel Rod Repairs)

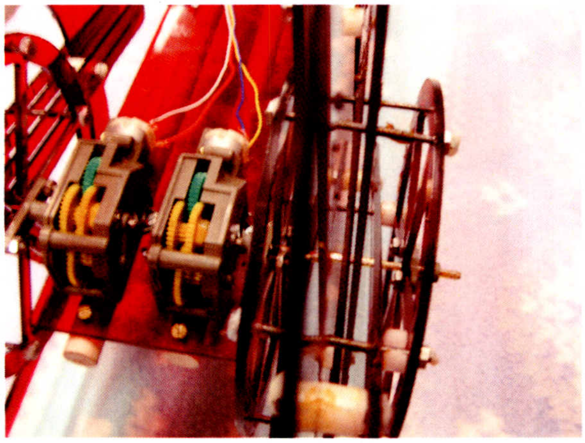
The bracing created a problem with the one of the walking pods because the legs could get hung up on the bracing. The solution was to create a set of plastic clips that were glued in place along the screws that transmit the torque from the hubs to the legs. The these clips secured the side to side motion of the legs which prevented the legs from becoming misaligned from the walker and hanging up on the bracing. (see Pic. 11)

One consequence of the plastic construction was that the body was extremely flexible. The flexibility was debilitating because I would flex the axel into a position were it would lock up the drive mechanism. In order to counteract the flexing two dowel rods were attached at the bottom to brace the body. (see pic 14) This eliminated the flexing.

The original design employed two ninety-degree brackets, screwed to the body to attach to the frame. An attempt to reduce the weight resulted in the brackets were not used. The attempt was to epoxy the frame and body directly together. This resulted in a skewed frame. An attempt to square the joint by using scrap plastic that was cut to ninety degree angels proved to be a failure because the joints were not strong enough. Finally the original plan of using commercial brackets was decided upon. The commercial brackets were not exactly he shape that was desired. As a result hot glue was employed as a filler.(see Pic. 11)

The motor boxes were built as recommended with the exceptions that the clutches were omitted and standard gears wee put in their places. Another exception was that the axels were not centered in the gearboxes. Instead the Axels were put off center in the gearboxes so that they could extend to the limits of the walking pod requirements. Both torque transmission arms were placed on the same sides of the gearbox.(see pic. 15) The problem was that the torque transmission arms had backings that only allowed for the arms to be placed on the ends of the axils. These backings were removed.

Picture 15



(Motor gearbox with offset axel)

The final objects were the power boxes. Two power boxes were employed with two channels each. This allowed for each motor to have its own channel. The only modification was that a 9 volt battery was taped in place in the place were two 1.5 volt C batteries were supposed to be used. This tripled the voltage.

14 Performance

The test of the walker's performance was as follows. The original tests simply tested if the walker worked. The initial tests showed that the legs motion did exist however because the frame was no square the walker often locked up. Later performance tests were conducted after the walker was made more ridged. The motors were shown to not behave well when they were linked on the same circuit. Whichever motor encountered the least resistance would spin while the motors that encountered more resistance would not move. This called for the requirement of a separate circuit for each motor so that each motor would have the same power output instead of splitting it between them. Another performance concern was that of voltage. While the power boxes were set up for a 3volt power supply it proved barley adequate for turning the legs. The motors were then tested with a 6 and 9 volt input. As well as an increase in the overall speed, torque was noted to have increased to the point where not all legs need be working for the walker to move. This did not appear to have the current ability to sustain walking. Other possibilities are a dc transformer or a considerably larger battery.

The walker is underpowered, however. The problem lies in the gearboxes and power demands. When the motor attempts to push the gearbox too far the gears fail and slip. This is destructive to the plastic gears. The walker cannot power itself entirely by one leg or lift its weight as desired. While the manufactured parts can handle the stresses with no noticeable deformation, the gearboxes cannot. One point this does illustrate about this design is that even though the gearboxes are not powerful enough to propel the walker with just one box. It illustrates that this design can continuously utilize all legs to perform a task, which is too difficult for them to perform individually. The problem iwtht he power is that the current is only available to power all motors for a short time. Afterwards the current can only power one or which is not adequate to propel the walker.

One unfortunate outcome of the walker is that the walker appeared adequately powered in the initial tests however. When all parts were assembled for the final test the walker did not live up to previous expectations. This happed too late in the project timeline to allow for the location of an alternate power source which is slow, light and powerful enough to perform said tasks.

15 Impact considerations

As with any design have impacts on many areas of life. Also the design must take into account many factors in manufacturing and usage. The factors that many engineers must take into account are Economic, environmental sustainability, manufacturability, ethical, health/ safety, political and social.

The first factor is economic. In an economic sense the walker can be more efficient. The design will allow for less energy wasted compared to that of other walkers. The walker does not waste energy in stopping and staring its members. Also because the walker is moving at a smooth level there is less energy spent in taking it over obstacles. This makes it more efficient on rough terrain.[15] As far as other equipment is concreted the walker may require no more control systems than a normal walking robot. It will still require more cost for control systems than a track or wheeled vehicle.

Another factor that influences the economic impact is the sustainability aspect. The working sustainability of any design dictates the economic feasibility of a design. The rollers and wells can be as sustainable as any walking device. The walker legs however can undergo a stress far greater than those of normal walkers because they can be forced to lift the walker in a pure bending action. In order to avoid fatigue failure the stress must be kept below the endurance limit. Other sustainability factors are the general cleanliness of the track the can reduce ware and the frictional forces in motion.

Manufacturability is another major factor in the economic feasibility of the design. The manufacturing is one of general assembly. In this demonstration design the parts can be made with a laser or water jet. The rest of the assembly is done with screws.

On a production model the parts could be manufactured on a larger scale and more weight.

Other factors besides the economic factors are the political factors. While the devise itself has no direct political implication, the political implications can result in its applications. The device can be used in outdoor applications such as logging which can be controversial.

Direct environmental issues result for the destruction of nature from the movement of the walker. The advantage of the walker it is that it only disturbs a small footprint. Wheels tend to crush all in their paths. Treads disturb even the soil under them. Walkers can step over plant material and only leave small disturbances.[16] Other environmental issues would be the exhaust and pollutants of the power supply. Because the walkers can navigate terrain easier, any pollution from a vehicle will be closer to natural settings.

Other considerations that can result in controversy are the safety factors. With any rotating objects the walkers can catch and pull in something loose, including a human limb or clothing. This can result in sever injury or loss of life. Guards should be installed around all moving parts. The driver should be positioned with a good view of all wells. All people involved with the equipment should be trained to avoid the machine when it is active.

Ethically the product is not controversial at all. Like any device it could be used by an unethical organization that disregards safety or other necessary concerns.

Socially the device will change little for humanity, as it does not create a new practice. It merely changes how people perform an old task.

16 Conclusion

The project is generally a success. The walker was intended only to display a working example of a cam driven walker and not perform any useful task. The goal of building a small structurally sound cam controlled walker capable of powering itself in a strait line was achieved. The walker also displayed the ability of the legs to work in unison. The walker however did not display the characteristics of being able to clear objects as well as desired. The underpowered nature of the walker made it difficult to clear objects. While it could still step over obstacles that were below the clearance height the walker could not climb an object as desired. The greatest problem lies in the scale of the walker. The walker is in a size range were plastic becomes too flexible and metal becomes to heavy for practical use. Also the power requirements of the motors are too great for small hobby motors, but larger commercial industrial motors would be too heavy for the frame. The prototype itself should have been made smaller to allow for weaker motors to power it as well as reduce the flexibility of the material involved. The next design based on the Cam controlled walker should be a larger design with a practical application. If made large enough to transport realistic loads then commercial motors and gear boxes could be utilized that would have plenty of power to propel the walker. Also the materials could be of heavier grade witch would allow for greater stability of the walker. An unmanned transport or remote operated robot would be a good next step. Depending on how the robot fairs larger human and heavier materials transporting systems could be constructed.

17 References

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Appendix

Appendix A: List of Citations.
Appendix B: MatLab programs used.
Appendix C: Pro Mechanica Stress-Strain images.
Appendix D: Auto Cad Pro Engineering Drawings.

Appendix A: List of citations

1 Wan, Xiaonan. *A Cam Controlled Single-Actuator- Driven Leg Mechanism For Legged Vehicles.* DeKalb IL. Department of Mechanical Engineering Northern Illinois University. 2004.p.12

2 Wan p.2

3 Wan p.2

4 Wan p.1

5 Wan p.12

6 Wan p.12

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8 Wan P.11

9 Wan p.58

10 Shigley, Joseph E. Mischke, Charles R. and Budynes Richard G. *Mechanical Engineering Design 7th. Ed.* New York. McGraw-Hill Inc. 2004 p.688

11 Ogota, Katshuhiko. *Modern Control Engineering 4th Ed.* Upper Saddle River, NJ. Prentice Hall Inc. 2002. p. 139

12 Shigley p. 260

13 Shigley p 263

14 "Acrylite literature," San Diego Plastics inc. (Accessed 11-27-2005) http://www.sdplastics.com/acrylit1.html

15 Wan p.2

16 Wan p.1

Appendix B: MatLab Programs

Program	Description
angles	Compare clearance heights and gait widths of different arc widths.
coords	Saves coordinate sets at specified intervals.
forces	Determines Forces on walker in any given time of motion.
paths	Gives the motion and track paths of the walker
xy	Gives track shape in x,y coordinates.

Angels

```
l=1;
limd=45;
for aspan=(limd+1):90;
thet=(1-aspan/180)*pi/2;
Max=0;
Maxh=0;
Maxd=0;
%annalizes all numbers
for count= 1:49;
   H=count*.01;%differing hieghts
   D=.005;
while (D<H);%differing leg spacers
   hi=(-H*cos(thet)/(sin(thet)^2))/(H/sin(thet)-D);
   lo=(-H*cos(thet)/(sin(thet)^2))/(H/sin(thet)-l+D);
   upper= atan(hi)/pi*180;
   lower= atan(lo)/pi*180;
   if ( (abs(upper) <= 45) && ( abs(lower) <= 45 ) );
      Max=D;
      if (Max>Maxd);
      Maxd=Max;
      Maxh=H;
   end
   end

   D=D+.005;
end
end
MD(aspan-limd)=Maxd;
MH(aspan-limd)=Maxh;
Ang(aspan-limd)=aspan;
stroke(aspan-limd)=2*sin(aspan/2*pi/180*Maxh);
```

```
diff(aspan-limd)=Maxh-Maxd;
perc(aspan-limd)=Maxd/Maxh;
end
%plot(Ang,MH)
hold on
%plot(Ang,MD)
plot(Ang,stroke)
hold off

%annalizes specific set of numbers
%plot(upper,lower)
thet=(1-span/180)*pi/2;
high=(-h*cos(thet)/(sin(thet)^2))/(h/sin(thet)-d);%upper track attack angle
low=(-h*cos(thet)/(sin(thet)^2))/(h/sin(thet)-l+d);%lower track attack angle
up= atan(high)/pi*180
down=atan(low)/pi*180
%d=distance from tip to slider
%l=total length of leg
%h= hight of axil off ground
%span=angle of gait
```

Coords

```
'output'
for i=0:89
   xargus=xfin(1+5*i)
   yargus=yfin(1+5*i)
end
```

Forces

```
l=.3;
h=l*.43;
d=l*.195;
s=.0555;
thet=ang/180*pi;
g=9.81;
width=.005;
%needs inputs angular vilocity(w),cart mass adjusted(M), leg
%mass(m),angle(ang)
dr= -h*cos(thet)*sin(thet)^(-2);
dr2=h*(sin(thet)^2+2*cos(thet)^2)*sin(thet)^(-3);
phi=-(atan(dr/(h/sin(thet)-l+d))+thet);
radhigh=abs(h/sin(thet)-l+d);
radfoot=h/sin(thet);
radtop=l-radfoot;
```

```
mainmat(1,1)=-sin(phi);
mainmat(1,2)=-cos(thet);
mainmat(1,3)=+cos(thet);
mainmat(1,4)=0;
mainmat(1,5)=0;

mainmat(2,1)=-cos(phi);
mainmat(2,2)=-sin(thet);
mainmat(2,3)=sin(thet);
mainmat(2,4)=0;
mainmat(2,5)=0;

mainmat(3,1)=-radhigh*sin(thet-phi);
mainmat(3,2)=-s;
mainmat(3,3)=-s;
mainmat(3,4)=cos(thet)*radfoot;
mainmat(3,5)=-sin(thet)*(radfoot+width);

mainmat(4,1)=cos(phi);
mainmat(4,2)=sin(thet);
mainmat(4,3)=-sin(thet);
mainmat(4,4)=0;
mainmat(4,5)=1;

mainmat(5,1)=sin(phi);
mainmat(5,2)=cos(thet);
mainmat(5,3)=-cos(thet);
mainmat(5,4)=1;
mainmat(5,5)=0;

answers(1,1)=M*g;
answers(2,1)=M*(dr2*w^2*cos(thet)-dr*w^2*sin(thet)+h*w^2+sin(thet)*w^2*dr2);
answers(3,1)=2*w^2*m*dr*(radtop-l/2);
answers(4,1)=m*(answers(2,1)/M-
dr2*w^2*cos(thet)+sin(thet)*dr*w^2+w^2*cos(thet)*(radtop-l/2)-dr*w^2*sin(thet));
answers(5,1)=m*(-w^2*(radtop-
l/2)*sin(thet)+dr*w^2*cos(thet)+dr2*sin(thet)*w^2+dr*w^2*sin(thet)+g);

mat1=mainmat;
mat2=mainmat;
mat3=mainmat;
mat4=mainmat;
mat5=mainmat;

for i=1:5;
```

```
    mat1(i,1)=answers(i);
    mat2(i,2)=answers(i);
    mat3(i,3)=answers(i);
    mat4(i,4)=answers(i);
    mat5(i,5)=answers(i);
end
fhigh=det(mat1)/det(mainmat)
f1=det(mat2)/det(mainmat)
f2=det(mat3)/det(mainmat)
N=det(mat4)/det(mainmat)
f=det(mat5)/det(mainmat)
torque=s*(f1+f2)
```

Paths

```
span=60
h=.43*l
d=.195*l

theta=span/360*pi+pi/2;
for i=1:101;
ang(i)= theta;
rfloor(i)=-h/sin(theta);%work foot path
rtop(i)=-h/sin(theta)+l;
rlow(i)=-h/sin(theta)+d;%work bearing center
rup(i)=-h/sin(theta)+l-d;
clearlow(i)=rlow(i)+bear;%work clearence path
clearup(i)=rup(i)-bear;

psiup=-atan((-h*cos(theta)/(sin(theta)^2))/(rup(i)));%upper contact angle

psilow=atan((-h*cos(theta)/(sin(theta)^2))/(rlow(i)));%lower contact angle


    trackup(i)=(rup(i)^2+bear^2-2*abs(rup(i))*bear*cos(pi-psiup))^.5;%upper track radius
    phiup(i)=-asin((bear)*sin(pi-psiup)/trackup(i))+ang(i);%upper track angle
    tracklow(i)=(rlow(i)^2+bear^2-2*abs(rlow(i))*bear*cos(pi-psilow))^.5;%lower track
radius
    philow(i)=asin((bear)*sin(pi-psilow)/tracklow(i))+ang(i)-pi;%lower track angle

    theta=theta-span/100*pi/180;
end

X=pi;
x=ang(1);
Y=d-l/2;
```

```
dY=0;
y=rlow(1);
dy=(h*cos(ang(1))/(sin(ang(1))^2));
B=-dy*(x-X)+(y-Y)-(dy-dY)*(x^3-X^3-3*x^2*(x-X))/(3*x^2-3*X^2);
B=B/(-2*(x-X)*(x^3-X^3-3*x^2*(x-X))/(3*x^2-3*X^2)+(x^2-X^2-2*x*(x-X)));
A=(-dY+dy-B*(2*x-2*X))/(3*x^2-3*X^2);
C=-3*A*x^2-2*B*x+dy;
D=-A*x^3-B*x^2-C*x+y;



%return paths.
for count=1:90-span/2+1;
  retang1(count)=span/360*pi+pi/2+pi/180*(count-1);%return track angle
  retang2(count)=pi-retang1(count);
  retlow(count)=A*retang1(count)^3+B*retang1(count)^2+C*retang1(count)+D;%return
track low
  dret=3*A*(retang1(count))^2+2*B*(retang1(count))+C;
  rethigh(count)=retlow(count)+l-2*d;%return track high

  rpsi1=atan(dret/retlow(count));%contact angle return track
  rpsi2=atan(dret/rethigh(count));%contact angle return track
  rtrack1(count)=-(retlow(count)^2+bear^2-2*bear*abs(retlow(count))*cos(pi-
rpsi1))^.5;%return track radius
  rtrack2(count)=(rethigh(count)^2+bear^2-2*bear*rethigh(count)*cos(pi-
rpsi2))^.5;%return track radius
  phi1(count)=-asin(bear*sin(pi-rpsi1)/abs(rtrack1(count)))+retang1(count);%return track
angle
  phi1op(count)=pi-phi1(count);%return track angle opposite
  phi2(count)=-asin(bear*sin(pi-rpsi2)/rtrack2(count))+retang1(count);%return track
angle
  phi2op(count)=pi-phi2(count);%return track angle opposite

  %Return foot paths
  retflow(count)=retlow(count)-d;
  retfhi(count)=rethigh(count)+d;
  %return inner clearence
  reclear1(count)=retlow(count)+bear;
  reclear2(count)=rethigh(count)-bear;

end
polar(ang,rfloor);%work foot path
hold on;
polar(ang,rlow);
polar(ang,rup);%work bearing center path
polar(ang,rtop);
```

```
polar(phiup,trackup);%work track path
polar(philow,tracklow);
polar(ang,clearlow);%work clearence
polar(ang,clearup);
polar(retang1,retlow);%return bearing center path
polar(retang1,rethigh);
polar(retang2,retlow);
polar(retang2,rethigh);
polar(phi1,rtrack1);%return track path
polar(phi2,rtrack2);
polar(phi1op,rtrack1);
polar(phi2op,rtrack2);
polar(retang1,retflow);%Return foot path
polar(retang1,retfhi);
polar(retang2,retflow);
polar(retang2,retfhi);
polar(retang1,reclear1);%return clearence
polar(retang1,reclear2);
polar(retang2,reclear1);
polar(retang2,reclear2);
hold off;
%d=distance from tip to slider
%l=total length of leg
%h= hight of axil off ground
%span is angle of gait
%bear bearing radius
```

xy

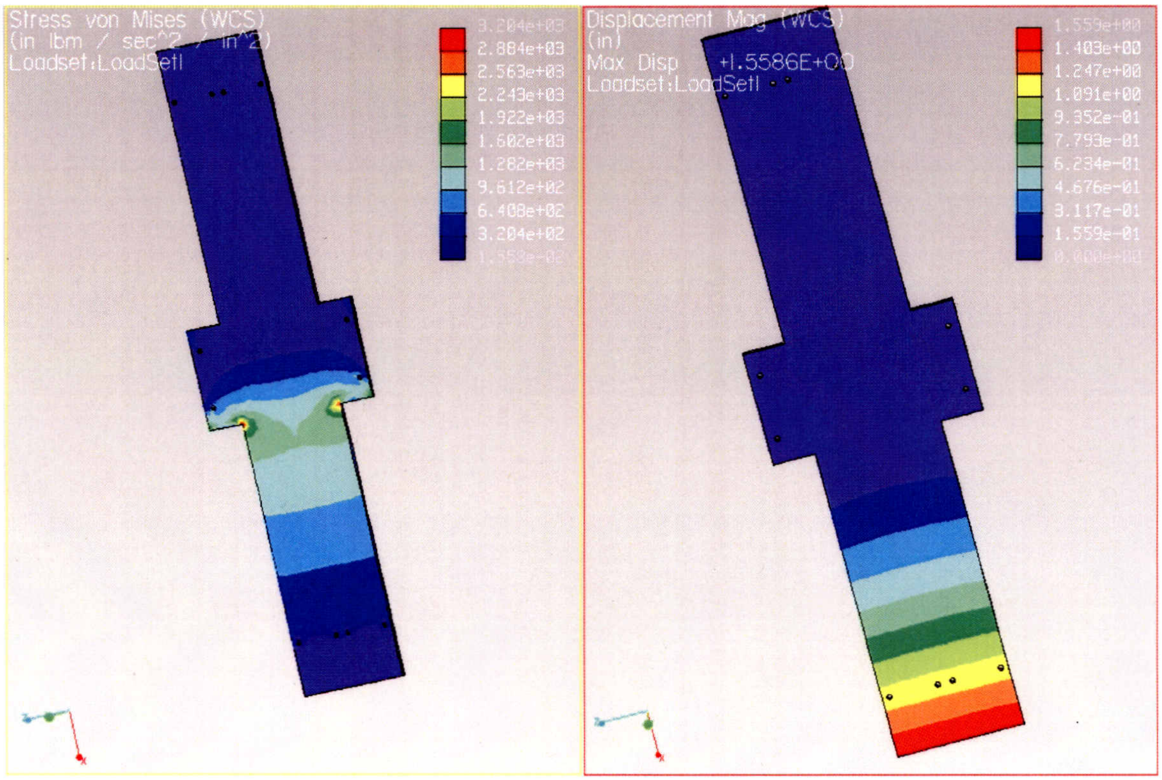
```
span=60
h=.43*l
d=.195*l

theta=span/360*pi+pi/2;
for i=1:101;
ang(i)= theta;
rfloor(i)=-h/sin(theta);%work foot path
rtop(i)=-h/sin(theta)+l;
rlow(i)=-h/sin(theta)+d;%work bearing center
rup(i)=-h/sin(theta)+l-d;
clearlow(i)=rlow(i)+bear;%work clearence path
clearup(i)=rup(i)-bear;

psiup=-atan((-h*cos(theta)/(sin(theta)^2))/(rup(i)));%upper contact angle

psilow=atan((-h*cos(theta)/(sin(theta)^2))/(rlow(i)));%lower contact angle
```

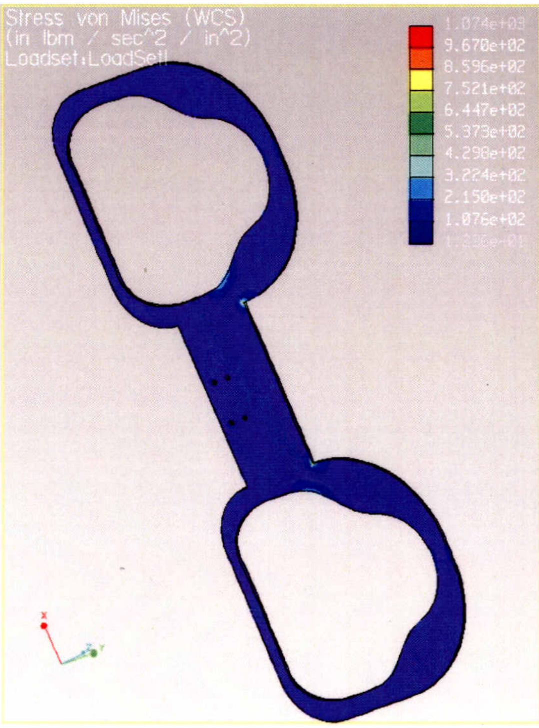
```
    trackup(i)=(rup(i)^2+bear^2-2*abs(rup(i))*bear*cos(pi-psiup))^.5;%upper track radius
    phiup(i)=-asin((bear)*sin(pi-psiup)/trackup(i))+ang(i);%upper track angle
    tracklow(i)=(rlow(i)^2+bear^2-2*abs(rlow(i))*bear*cos(pi-psilow))^.5;%lower track
radius
    philow(i)=asin((bear)*sin(pi-psilow)/tracklow(i))+ang(i)-pi;%lower track angle

    theta=theta-span/100*pi/180;
end

X=pi;
x=ang(1);
Y=d-l/2;
dY=0;
y=rlow(1);
dy=(h*cos(ang(1))/(sin(ang(1))^2));
B=-dy*(x-X)+(y-Y)-(dy-dY)*(x^3-X^3-3*x^2*(x-X))/(3*x^2-3*X^2);
B=B/(-2*(x-X)*(x^3-X^3-3*x^2*(x-X))/(3*x^2-3*X^2)+(x^2-X^2-2*x*(x-X)));
A=(-dY+dy-B*(2*x-2*X))/(3*x^2-3*X^2);
C=-3*A*x^2-2*B*x+dy;
D=-A*x^3-B*x^2-C*x+y;



%return paths.
for count=1:90-span/2+1;
   retang1(count)=span/360*pi+pi/2+pi/180*(count-1);%return track angle
   retang2(count)=pi-retang1(count);
   retlow(count)=A*retang1(count)^3+B*retang1(count)^2+C*retang1(count)+D;%return
track low
   dret=3*A*(retang1(count))^2+2*B*(retang1(count))+C;
   rethigh(count)=retlow(count)+l-2*d;%return track high

   rpsi1=atan(dret/retlow(count));%contact angle return track
   rpsi2=atan(dret/rethigh(count));%contact angle return track
   rtrack1(count)=-(retlow(count)^2+bear^2-2*bear*abs(retlow(count))*cos(pi-
rpsi1))^.5;%return track radius
   rtrack2(count)=(rethigh(count)^2+bear^2-2*bear*rethigh(count)*cos(pi-
rpsi2))^.5;%return track radius
   phi1(count)=-asin(bear*sin(pi-rpsi1)/abs(rtrack1(count)))+retang1(count);%return track
angle
   phi1op(count)=pi-phi1(count);%return track angle opposite
   phi2(count)=-asin(bear*sin(pi-rpsi2)/rtrack2(count))+retang1(count);%return track
angle
   phi2op(count)=pi-phi2(count);%return track angle opposite
```

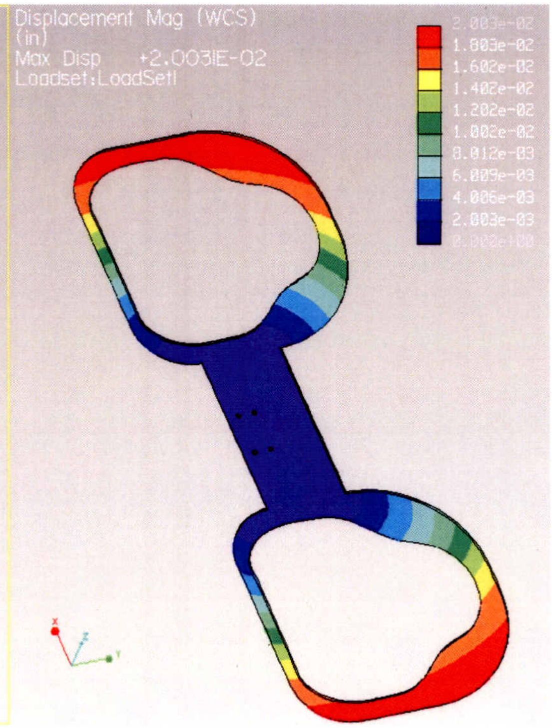
```
  %Return foot paths
  retflow(count)=retlow(count)-d;
  retfhi(count)=rethigh(count)+d;
  %return inner clearence
  reclear1(count)=retlow(count)+bear;
  reclear2(count)=rethigh(count)-bear;

end
polar(ang,rfloor);%work foot path
hold on;
polar(ang,rlow);
polar(ang,rup);%work bearing center path
polar(ang,rtop);
polar(phiup,trackup);%work track path
polar(philow,tracklow);
polar(ang,clearlow);%work clearence
polar(ang,clearup);
polar(retang1,retlow);%return bearing center path
polar(retang1,rethigh);
polar(retang2,retlow);
polar(retang2,rethigh);
polar(phi1,rtrack1);%return track path
polar(phi2,rtrack2);
polar(phi1op,rtrack1);
polar(phi2op,rtrack2);
polar(retang1,retflow);%Return foot path
polar(retang1,retfhi);
polar(retang2,retflow);
polar(retang2,retfhi);
polar(retang1,reclear1);%return clearence
polar(retang1,reclear2);
polar(retang2,reclear1);
polar(retang2,reclear2);
hold off;
%d=distance from tip to slider
%l=total length of leg
%h= hight of axil off ground
%span is angle of gait
%bear bearing radius
```

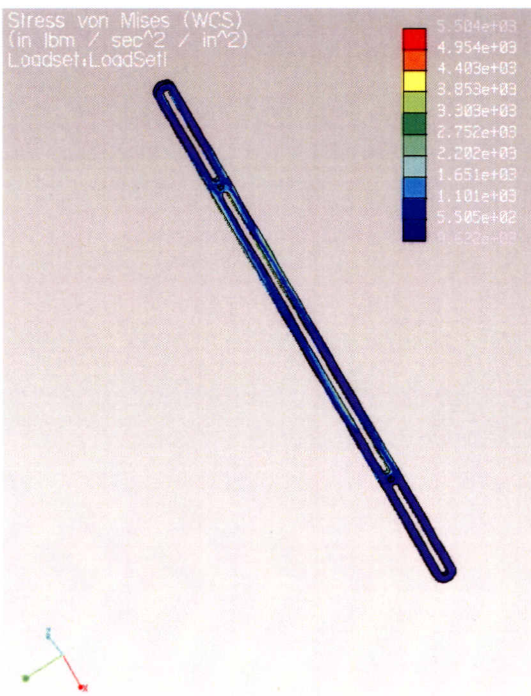
Appendix C: pro mechanica Stress-Strain Images

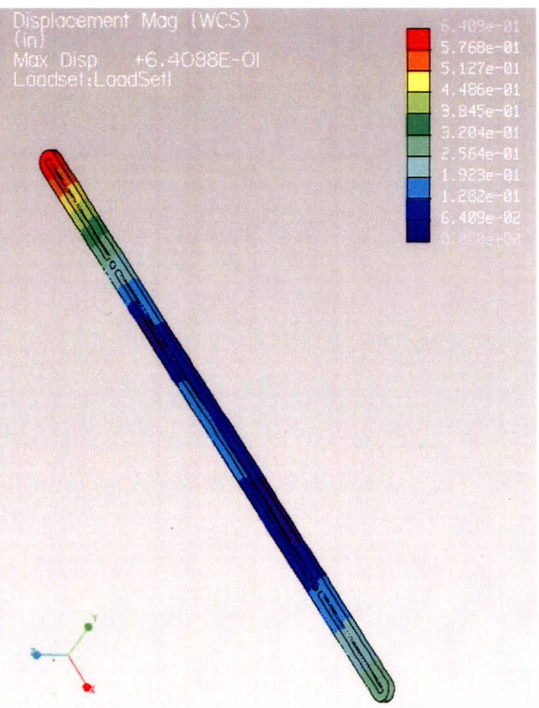
Image
Body With 2.2 lb force
Wells at top of arch
1cm leg during lifting
1.5 cm leg during lifting
Wells during lifting

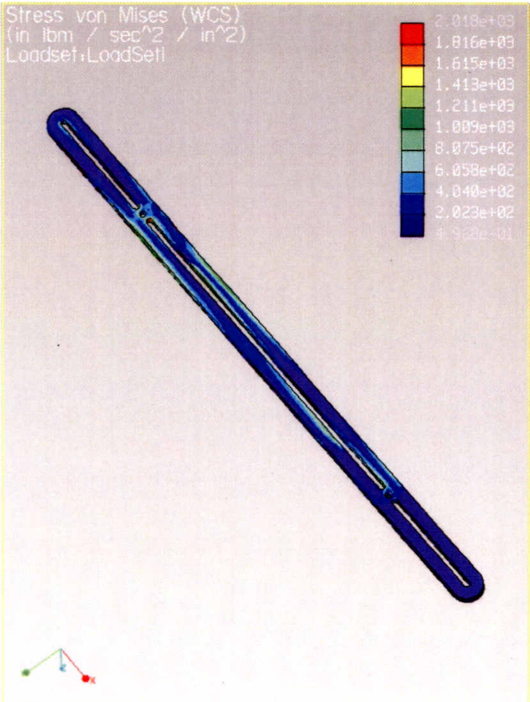


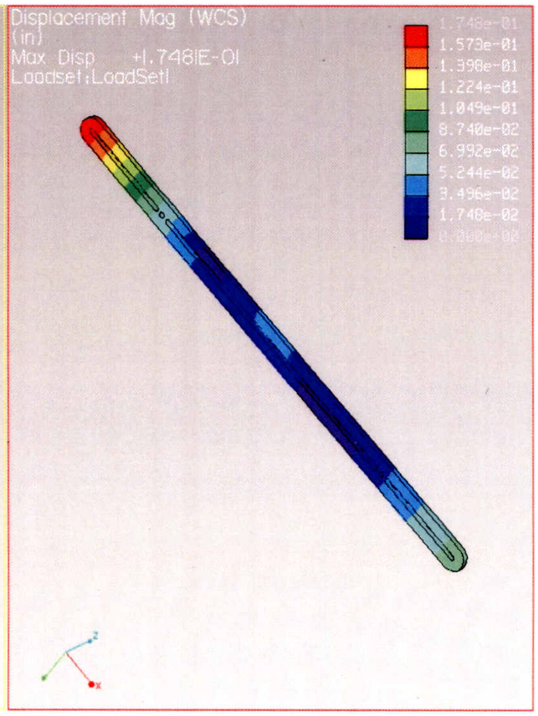

Stress von Mises (WCS)
(in lbm / sec^2 / in^2)
Loadset:LoadSet1
1.074e+03
9.670e+02
8.596e+02
7.521e+02
6.447e+02
5.373e+02
4.298e+02
3.224e+02
2.150e+02
1.076e+02

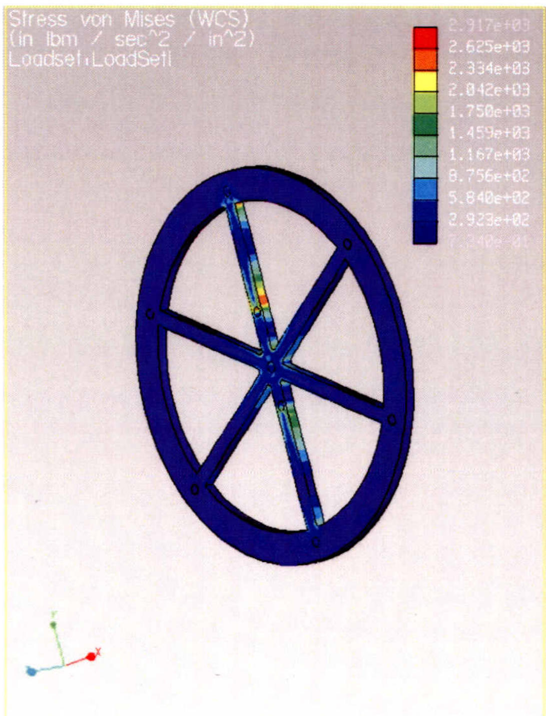

Displacement Mag (WCS)
(in)
Max Disp +2.0031E-02
Loadset:LoadSet1
2.003e-02
1.803e-02
1.602e-02
1.402e-02
1.202e-02
1.002e-02
8.012e-03
6.009e-03
4.006e-03
2.003e-03

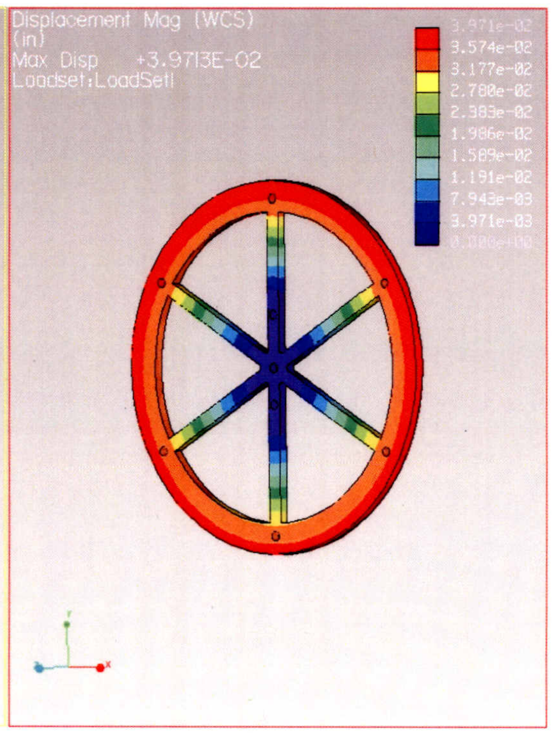

Stress von Mises (WCS)
(in lbm / sec^2 / in^2)
Loadset:LoadSet1
5.504e+03
4.954e+03
4.403e+03
3.853e+03
3.303e+03
2.752e+03
2.202e+03
1.651e+03
1.101e+03
5.505e+02


Displacement Mag (WCS)
(in)
Max Disp +6.4088E-01
Loadset:LoadSet1
6.409e-01
5.768e-01
5.127e-01
4.486e-01
3.845e-01
3.204e-01
2.564e-01
1.923e-01
1.282e-01
6.409e-02


Stress von Mises (WCS)
(in lbm / sec^2 / in^2)
Loadset:LoadSet1
2.018e+03
1.816e+03
1.615e+03
1.413e+03
1.211e+03
1.009e+03
8.075e+02
6.058e+02
4.040e+02
2.023e+02
x

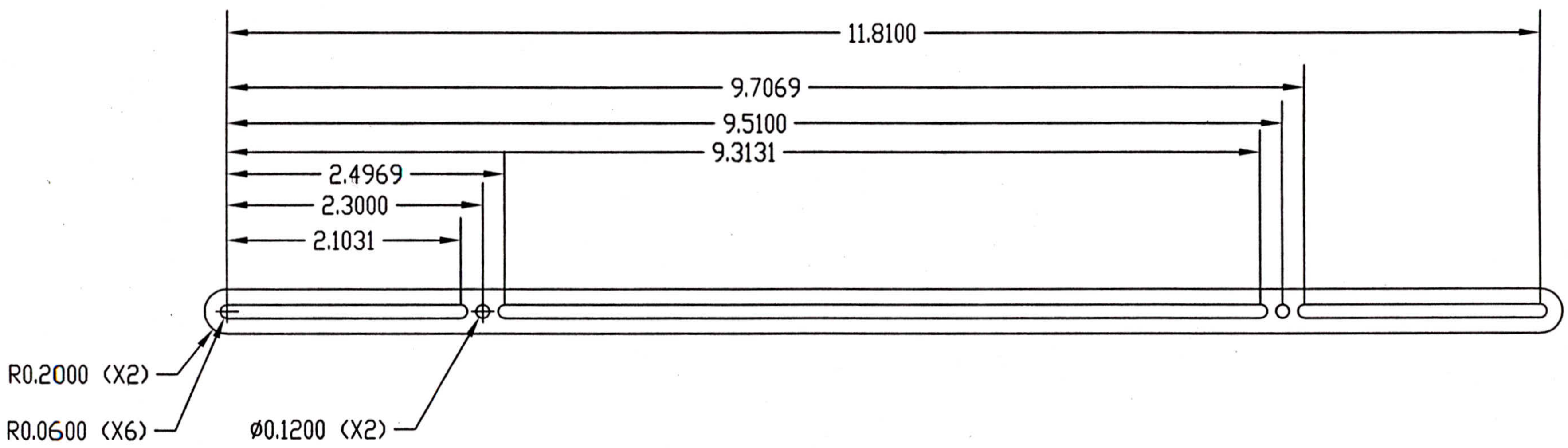

Displacement Mag (WCS)
(in)
Max Disp +1.7481E-01
Loadset:LoadSet1
1.748e-01
1.573e-01
1.398e-01
1.224e-01
1.049e-01
8.740e-02
6.992e-02
5.244e-02
3.496e-02
1.748e-02
0.000e+00
z
x


Stress von Mises (WCS)
(in lbm / sec^2 / in^2)
Loadset:LoadSet1
2.917e+03
2.625e+03
2.334e+03
2.042e+03
1.750e+03
1.459e+03
1.167e+03
8.756e+02
5.840e+02
2.923e+02
Y
X

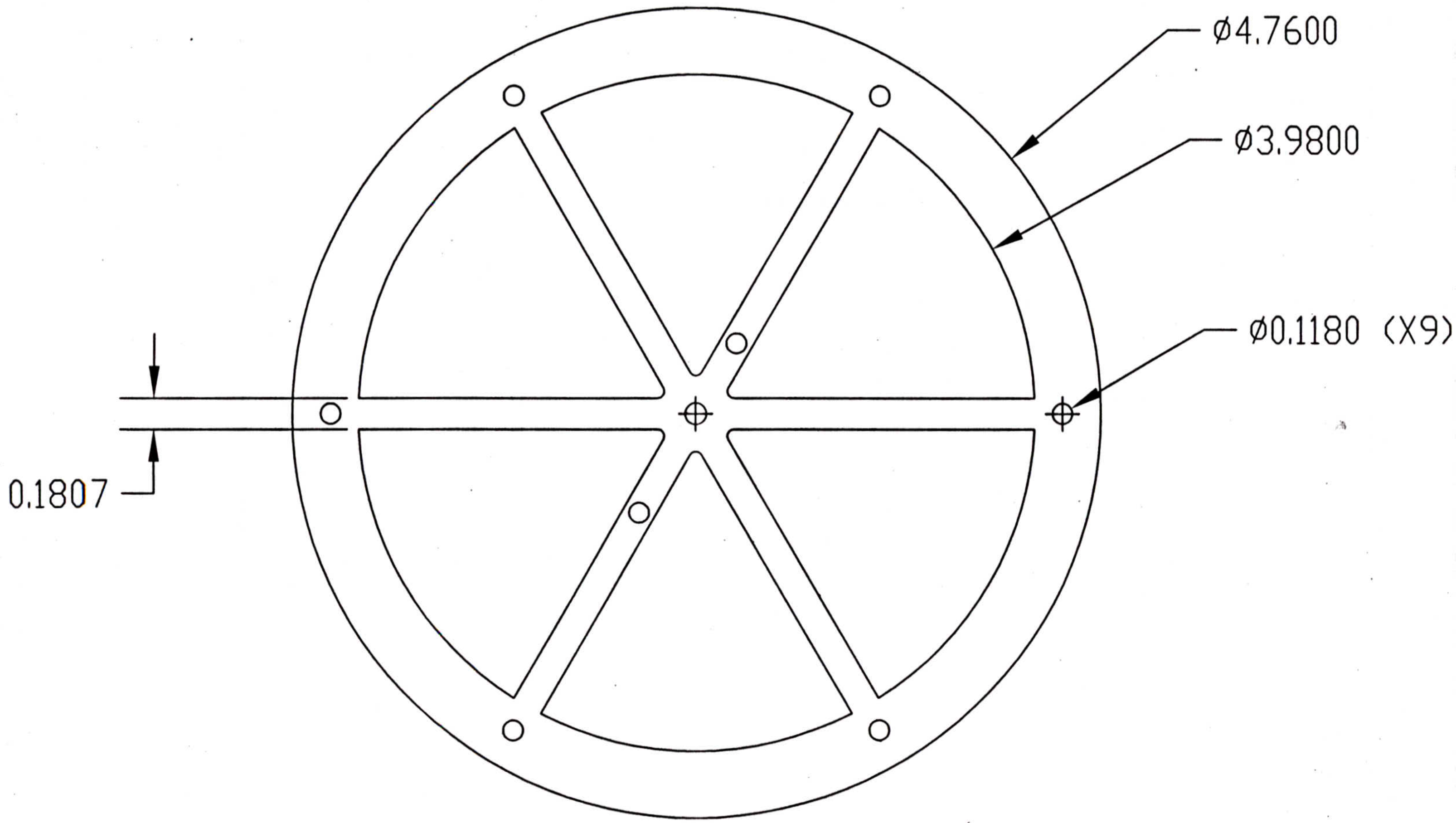

Displacement Mag (WCS)
(in)
Max Disp +3.9713E-02
Loadset:LoadSet1
3.971e-02
3.574e-02
3.177e-02
2.780e-02
2.383e-02
1.986e-02
1.589e-02
1.191e-02
7.943e-03
3.971e-03
0.000e+00
Y
X

Appendix D: Auto Cad/Pro Engineering Drawings.

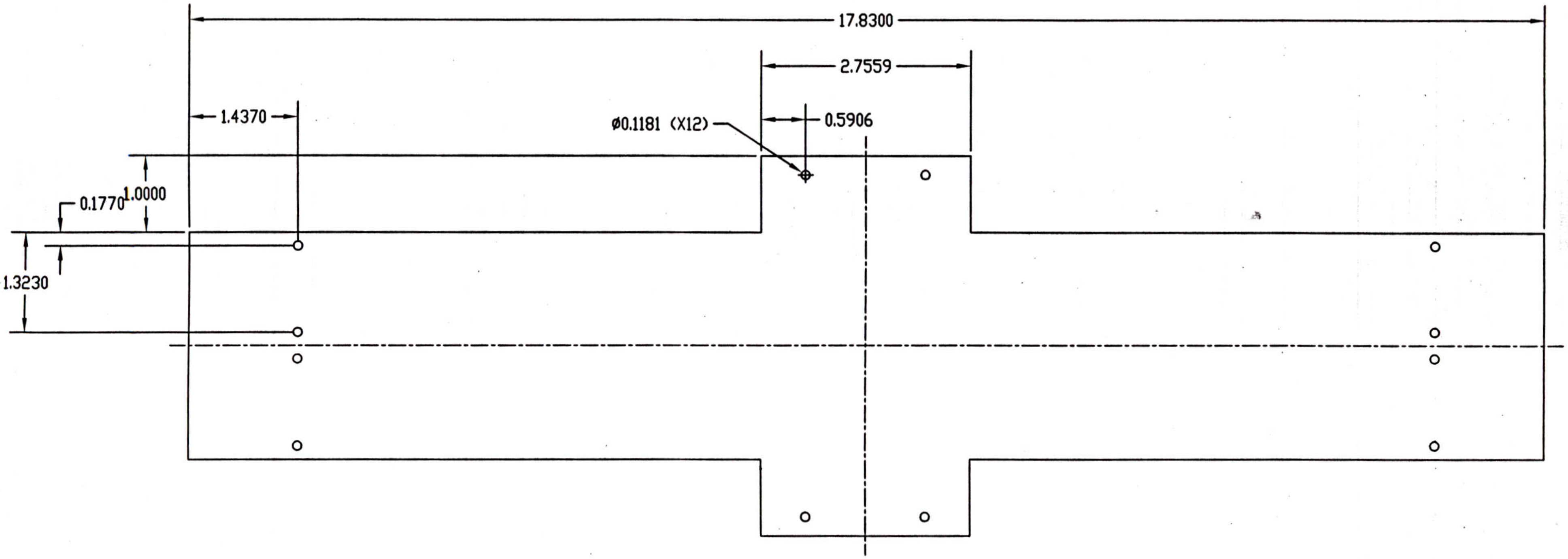
1 Walker Leg
2Walker Hub
3 Walker Body
4 Walker Wells
5 Leg Spacer



Cam Walker Leg	
Department Of Mechanical Engineering Northern Illinois University DeKalb IL 60115	
Matrial: 1/8 in Acrylic	Scale 1.5:1
11/30/2005	Andrew Crow



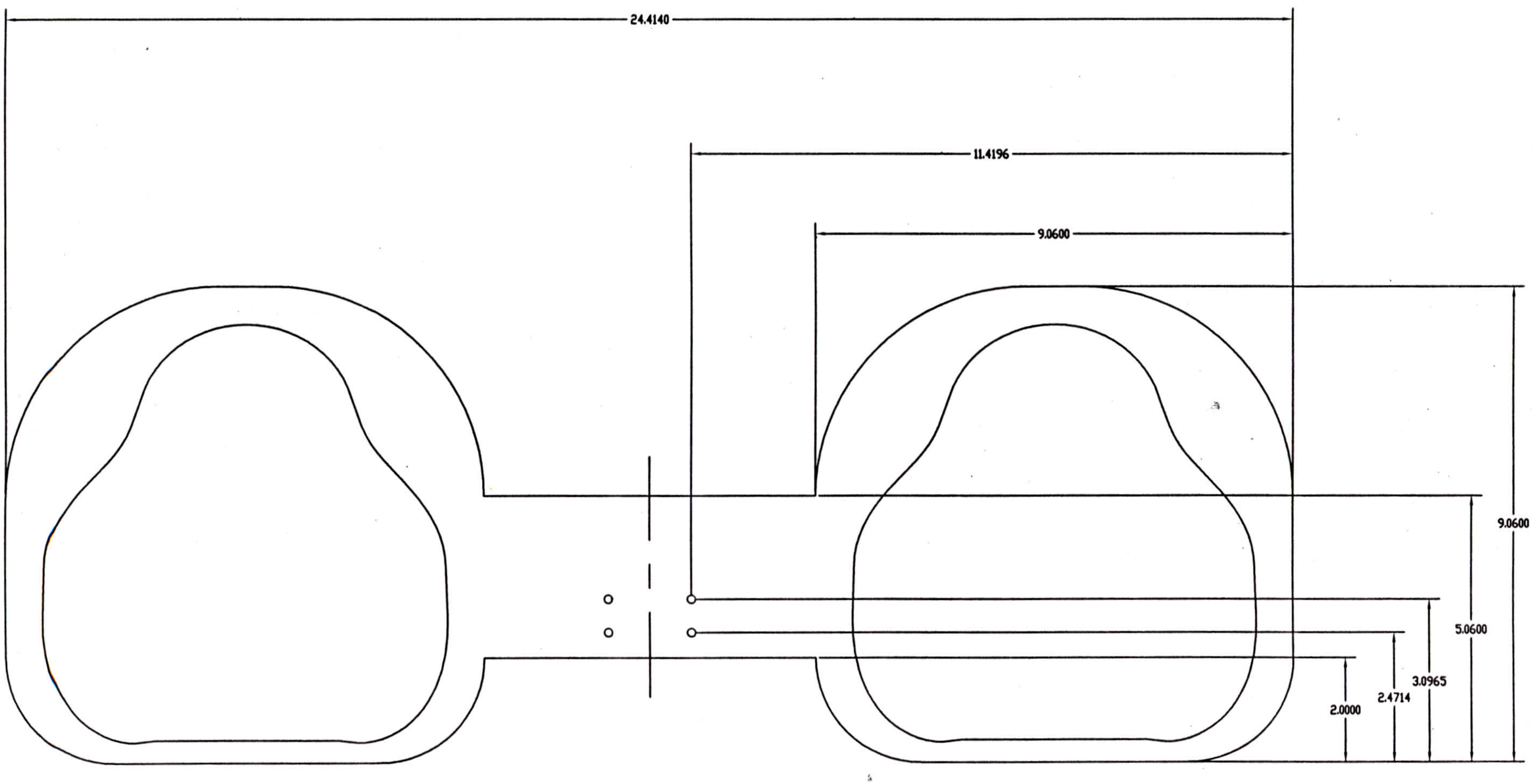
Cam Walker Hub	
Department Of Mechanical Engineering Northern Illinois University DeKalb IL 60115	
Matrial: 1/8 in Acrylic	Scale 1:1
11/30/2005	Andrew Crow



Cam Walker Base

Department Of Mechanical Engineering
Northern Illinois University
DeKalb IL 60115

Matrial: 1/8 in Acrylic	Scale 2:1
11/30/2005	Andrew Crow



Cam Walker Wells	
Department Of Mechanical Engineering Northern Illinois University DeKalb IL 60115	
Matrial: 1/8 in Acrylic	Scale 3:1
11/30/2005	Andrew Crow

Cam Walker Spacer	
Department Of Mechanical Engineering Northern Illinois University DeKalb IL 60115	
Matrial: 1/2 In Durland Rod	Scale 1:1
11/30/2005	Andrew Crow