State University of New York at Buffalo

Department of Mechanical and Aerospace Engineering.

MAE 412: MACHINES & MECHANISMS II

PROJECT REPORT
FOR
BALL LAUNCHING MECHANISM

SUBMITTED BY GROUP 7

DATE: DECEMBER 14, 2001.

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BALL LAUNCHING MECHANISM FOR MAE412 PROJECT
TECHNICAL REPORT

INTRODUCTION:

The goal of this project is to develop a catapult system that will be used to throw a squash ball the farthest distance possible while meeting the design constraints given. The cost of developing this mechanism is minimized to less than 30 dollars. The mechanism that we have created performs well and meets all the constraints.

Constraints on the design were formulated as follow:

a. The mechanism should incorporate at least one 4-bar mechanism.
b. The motor is specified. The details are given in the Appendices.
c. The entire system must be made of wood.
d. The entire mechanism must operate within a window of 2ft x 2ft. The operating window must include the entire base plate.
e. The mechanism should be mounted on a base plate such that it can quickly clamped onto a table.
f. No parts of the mechanism should cross the start plane.
g. Position, velocity, and acceleration analysis using techniques learned in class must be possible for the model chosen.
h. If a spring is used, it cannot be preloaded. That is, no preloaded potential energy.
i. No magnets, chemical reactions, or biological sources of energy can be used.
j. The device must be designed, built, and tested in the allotted time.
k. For the competition, only the flipping of a switch can operate the mechanism. Everything else, including ball release, must be accomplished by the mechanism.

DESIGN PROCESS:

We begin our design of the mechanism by divided into four different sub-groups. The responsibilities of each sub-groups was documented in the Project Proposal. We begin our process in the following manner:

First week (11/11-11/16)
Idea generation and work distribution week.

a. Manufacturing group will have to build the motor and test the motor.
b. Manufacturing group will test the elastic sensitivity of the rubber band.

c. Analysis Group will have to find out the four bar mechanism to be use, the solution for the release mechanism and the 2 revolution constrain.
d. Virtual Prototype will have to start learning how to use ADAMS and draw a model of our design.
e. Manufacture group should have solution for the joints, links that we are going to use, and prepare them in advance.

Second week (11/17-11/23)
Analysis and virtual prototype week.

a. Virtual Prototype group will have to use ADAMS to run the Mechanism. Come out with a details design of the mechanism.
b. The model should be give to the Manufacturing group by 11/22.
c. Manufacturing group should prepare all the materials that going to use for the model.
d. The report-writing group should arrange their report and type in Microsoft Words.

Third week (11/22-11/29)
Manufacture week.

a. Start manufacturing the model. The model should be available on 11/29. The testing process will then begin.
b. The report writing should come out with an outline of the final report.

Fourth Week (11/29-12/7)
Testing and model modified week.

a. Manufacturing group will start testing the model and do the statistic testing for the model. Determine the performance of the model, and compare the result with the calculated value.
b. Prepare for the competition.
c. Report for each group should be ready.

Fifth Week (12/7-12/14)
Report writing week.

a. Each report writing person should have prepared the report for each sub-group.
b. Combine the report from each group will be perform and finalized.

Overall Ideas Generation & Design Process:

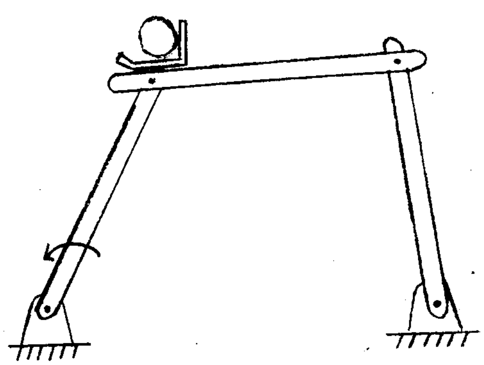
In this section, we divided into four stages to describe how we process our design. These four sections are:

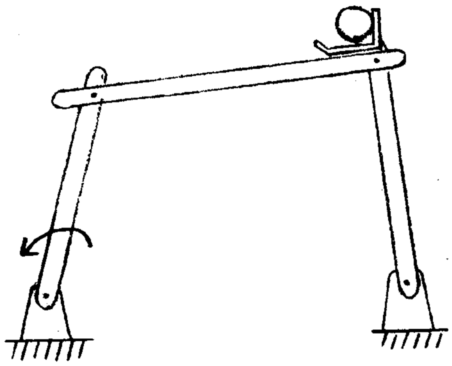
A. Idea Generation Process.
B. Analysis Process.
C. Virtual Analysis Process.
D. Manufacturing Process.

Each of this stage is describe as follow:

1. Idea Generation Process.

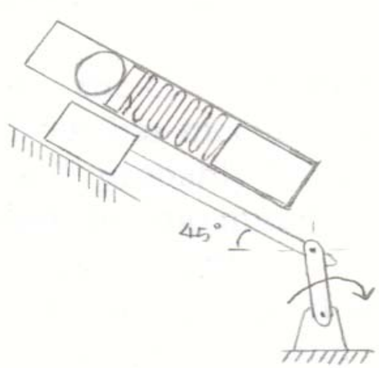
In order to create a mechanism for the competition, several concept mechanisms needed to be created to discuss within the group. In order to facilitate the creative process, each member of the group was required to come up with three different models and then present them to the group. After each group member presented his ideas, the entire group brainstormed on the feasibility of the concept. Questions would inevitably arise about the design, performance, and construction of the model. Several concepts were discussed and evaluated.

Model 1	Description
	By using a four bar mechanism, we put the motor at the input link, the holder of the ball at some position on the input link. The mechanism will be a double-rocker. When the motor turns the input link to a certain distance, the follower will limit the motion of the input and release the ball. The release angle will need to be determining by using the analysis method.

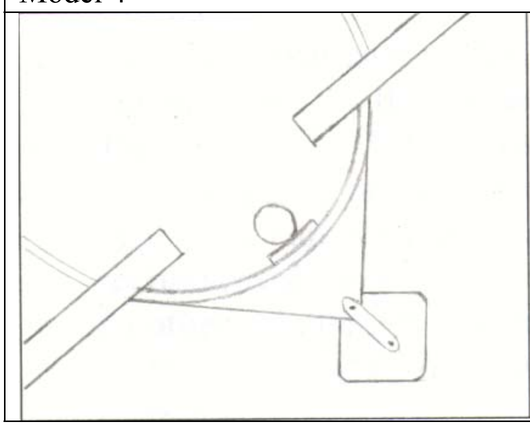
Model 2	Description
	This model is basically looks the same as the first model that we have come up with. Only that the ball holder is attached to the follower. This required a crank rocker for the four bar mechanism. The motor will be attached to the input link. At some point, the ball will be released. This model required the well control of the power of the motor and we need the motor to turn for speed, because the limitation of two revolutions is given. We decided not to use this model.

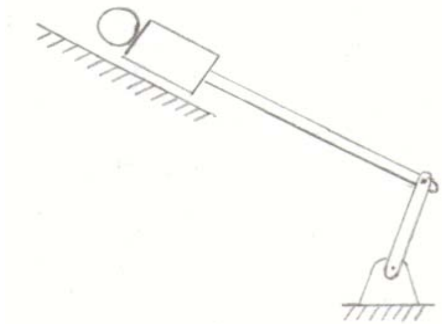
One model consisted of a basic four-bar mechanism. It would be a double-rocker with the motor driving the input link. The ball would be mounted in a holder that was attached to the input link. This model was extremely simple and would be very easy to construct and analyze. However, its major disadvantage was that it did not provide a mechanical advantage. The motor would be driving the four-bar, but the mechanism did not make full use of the motor output. This model was not further developed.

The second model that was presented was very similar to the first model with one minor modification. The ball would now be placed in a holder mounted to the follower (output) link. This was a significant improvement over the first model. It would take advantage of the motor output by using the entire four-bar to launch the ball, not just the input link. It would also cause less strain on the motor due to its configuration. However, this model was not developed because there was no energy storing devices like springs or weights. If utilized correctly, these devices would greatly improve the performance of the mechanism.

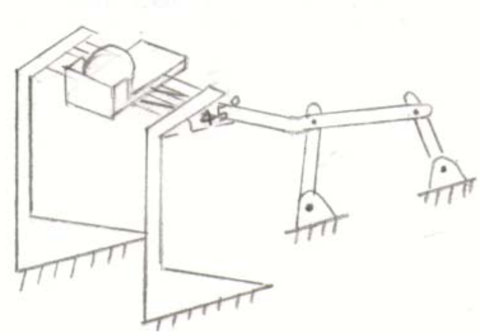
Model 3	Description
	This model uses the combination of a spring and a slider to pull the spring to a certain distance and release it. The problem of this model is that we need a motor that is able to pull the spring, the friction in the pulling process will reduced the power that the motor deliver, and it is not easy to manufacture. Furthermore, we cannot think if a good idea to disconnect the slider and the spring.

The third model that was presented consisted of a slider-crank mechanism and a spring. The slider would compress the spring and when the spring was fully compressed, the mechanism would release and launch the ball. This model was a great improvement over previous ideas. It took advantage of stored energy and it could launch the ball at a predetermined angle. The disadvantages of this model were very major. There were several variables in the construction of the model. Friction between the slider and the sliding surface was a major concern because of the relatively small output of the motor. Any friction losses would be devastating to the performance of the mechanism. Also, it became difficult to linearly compress the spring. Any change in the spring compression angle would change the behavior of the mechanism. It was also difficult to create a release mechanism for the model. Specifically, how to release the slider once the spring was fully compressed. This model was promising, but several issues made it not feasible with the limited time for the project. If more time was available, it could be pursued further.

Model 4	Description
	This model is basically a catapult system with a motor pulling the two links that is attached to the ground. There is an elastic band that connects the links and the motor pulls the links back to the corner. The problem for this model is that it has too many variables that make the analysis very complicated. Furthermore, we cannot think of a good solution for the cutting of the cord that pulls the bar to release the ball.

Model 5	Description
	This model basically uses the slider to push the ball when the slider moves. The advantages of this model are that the release angle for the ball is easy to fix. However, the slider moving path is not easy to determine, we need to gives the slider a path to move. This will in turns create a lot of friction that reduces the power of the motor.

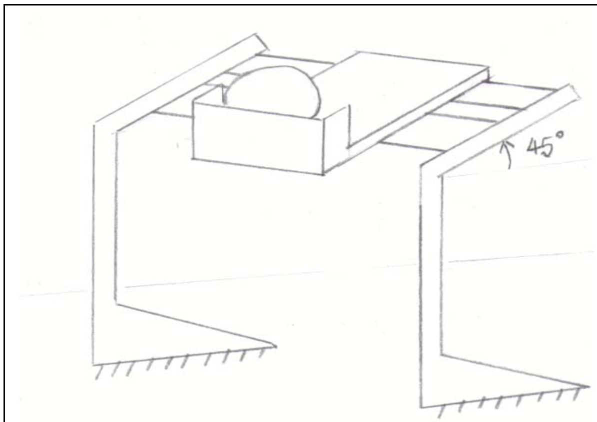
There are another two models being discussed and considered. These models was shown and discussed in model 4 and 5 above. The final model that we will base on is model 6. The model that was constructed consisted of a four-bar mechanism that would pull elastic and release. The four-bar would be driven by the motor connected to the input link. The ball would be launched from a holder mounted to the mechanism that would assure a launch angle of approximately 45° from the horizontal. The elastic would be attached to the joint between the coupler link and follower link. The release mechanism was not yet clear at this stage, but a preliminary gearing concept was created to release the mechanism. Elastic was chosen because it would be easy to work with. Elastic could be added or subtracted to create the correct spring constant. It was a very modular design feature that was a major advantage. After some discussion, it was decided that this would be the model to further develop.

Model 6	Description
	This model is basically the combination of a catapult system with a four bar mechanism that pull the catapult system. This model is easy to manufacture and we can determine the motion of the four bars, as we desired it to move by using synthesis method. We decided to use this model for our project. Below are the descriptions of this model.

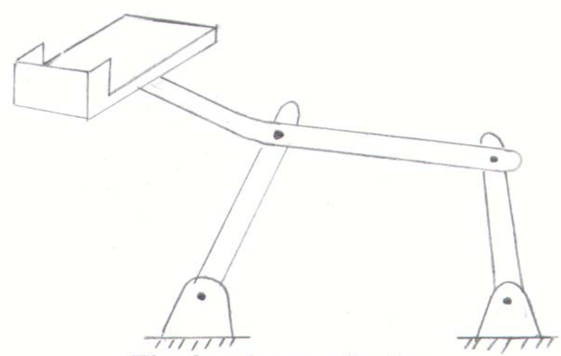
After considering the advantages of these models, we are considering the use of model 6 as our design model. This model has the following advantages:

a. It uses the elastic materials to store the energy while the motor is used to drive the four bar mechanism to pull the elastic materials. The elastic material that we will probably use is a rubber band. The advantage of using the rubber band is that the maximum amount of energy produced by the motor can go into the flight of the ball.
b. Another advantage of using this model is that it is easy to construct.
c. We will basically find out the maximum torque that the motor can have after we get the motor. Then we will have to determine the elastic sensitivity of the rubber band that we are going to use. The Manufacturing group will do this entire task.
d. Another advantage of this material is that we can easily determine the angle that we want the ball to leave the system.
e. The challenge of this model is how we can make use of the advantage of 2 revolutions to fully stretch the rubber band. After the first turn of the input link, how can we maintain the pulled distance and continue to pull it in the second revolution.
f. Another challenge of this problem will be the design of the release mechanism. This must release the ball after the motor has turned for two revolutions.

The more details of the two separate systems are shown bellow:



The catapult system


The four bar mechanism

However, after the Analysis Process is started, we have modified this model according to the analysis result. This process was shown in the following.

2. Analysis Process:

The main responsibilities of the analysis group were to analyze models of the mechanism and evaluate its performance characteristics. The first analysis performed by the group was to create a general mechanism layout after the brainstorming phase was completed and a model was chosen. This was performed in MATLAB using the synthesis method. The constraints on the model were its size in order to fit in the 2 ft. X 2 ft. window and the starting and ending positions of the mechanism. Using MATLAB many different arrangements for the mechanism's links were created.

The synthesis portion of the project consisted of using Matlab to determine which configurations could be possible given our constraints of size and starting and ending positions of the mechanism. Figure 2-1 shows the output from the Matlab program for the two limiting positions that were the constraints.

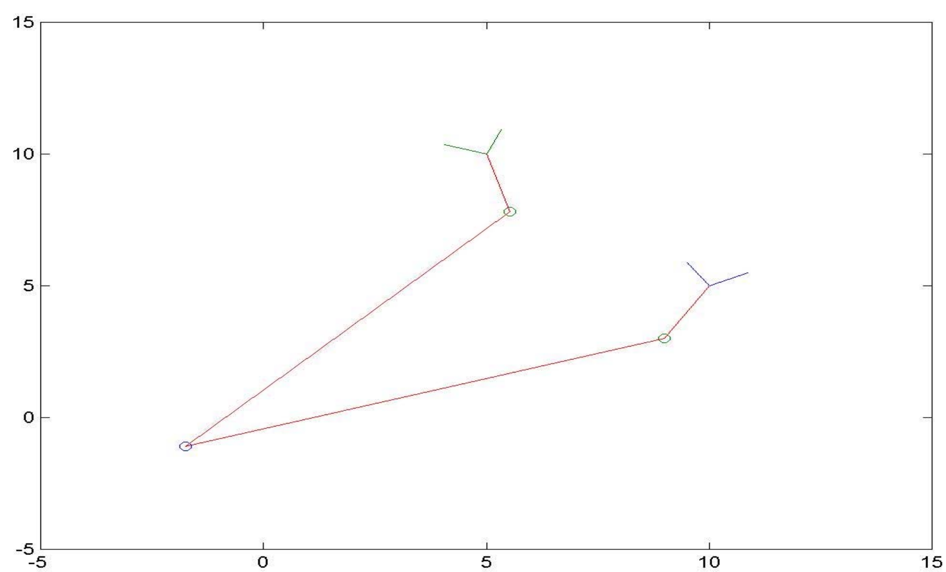


Figure 2-1. MATLAB generated graph use in synthesis method.

Figure 2-2 shows one of the configurations produced from Matlab. This was determined to not be a good model because of the crossed configuration at one of the limiting positions. This model was not to be used.

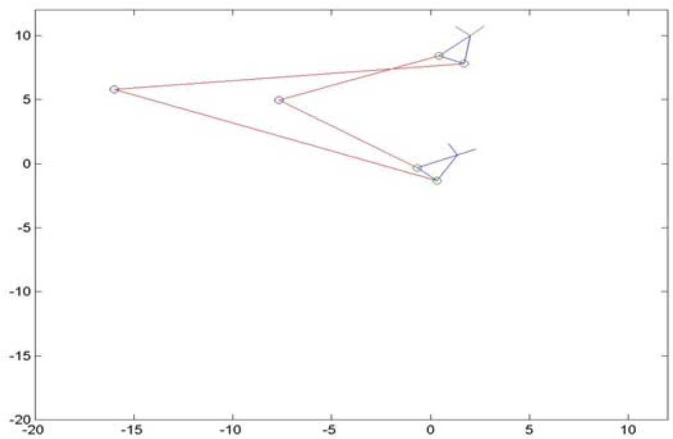


Figure 2-2. Graph generated using MATLAB show the cross configuration of the 4 bars.

These were narrowed down after review. Several configurations consisted of a crossed links. These were not considered because of the difficulty in manufacturing a mechanism that would go from an uncrossed to crossed configuration. Also, these configurations would provide no mechanical advantage over other models. Other models produced from the synthesis method were not considered because they did not meet the size constraint of the system. This constraint eliminated many of the models that were generated and allowed the analysis to be performed on only a few of the synthesis models. The final three models were reviewed by the group and one mechanism was chosen as the preliminary model. This model was shown in Figure 2-3. This model would be analyzed and evaluated before it would be manufactured.

Figure 2-3 shows the one of the final models considered for manufacture. It shows the general layout of the mechanism. It is a rough estimation but it showed how the mechanism could be constructed and not has any of the drawbacks of other configurations like the crossed configuration of Figure 2-2.

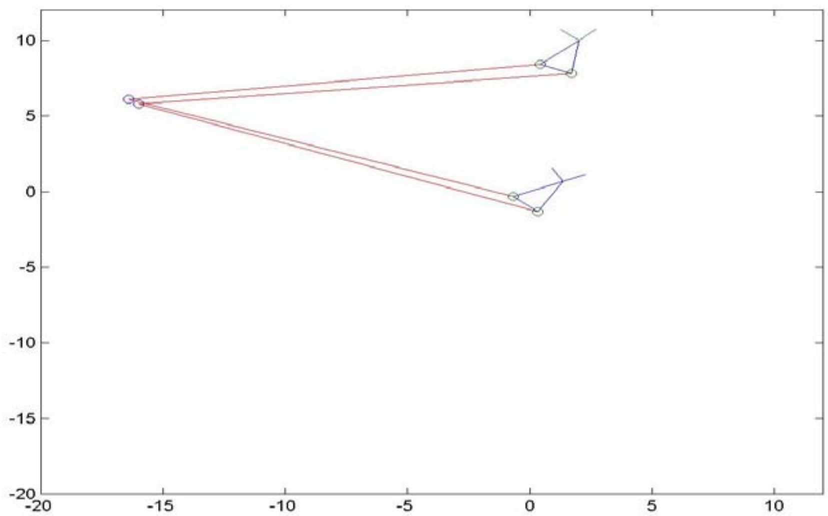


Figure 2-3. General layout of the model.

The next step of the process was to animate the model using MATLAB. This was needed in order to visualize the movements of the mechanism. This was a way to inspect the motion of the mechanisms and determine whether it would fit the characteristics that were required. Also, it would be a valuable tool during the manufacturing process. If any changes needed to be made during manufacture, it could be observed in MATLAB before any physical changes were implemented.

Once the synthesis analysis was performed and a few preliminary models were chosen, a MATLAB animation of the model was created in order to visualize its motion. It would also be very useful if any changes needed to be made to the model. Any changes could be simulated in MATLAB before manufacturing. Some of the results generated using MATLAB were shown below

The animation part created using MATLAB was shown in the next page. Figures 2-4 through 2-6 show the final mechanism at three different times in its motion. Figure 2-4 is at the starting position of the mechanism. Figures 2-5 and 2-6 are at two later times in the animation.

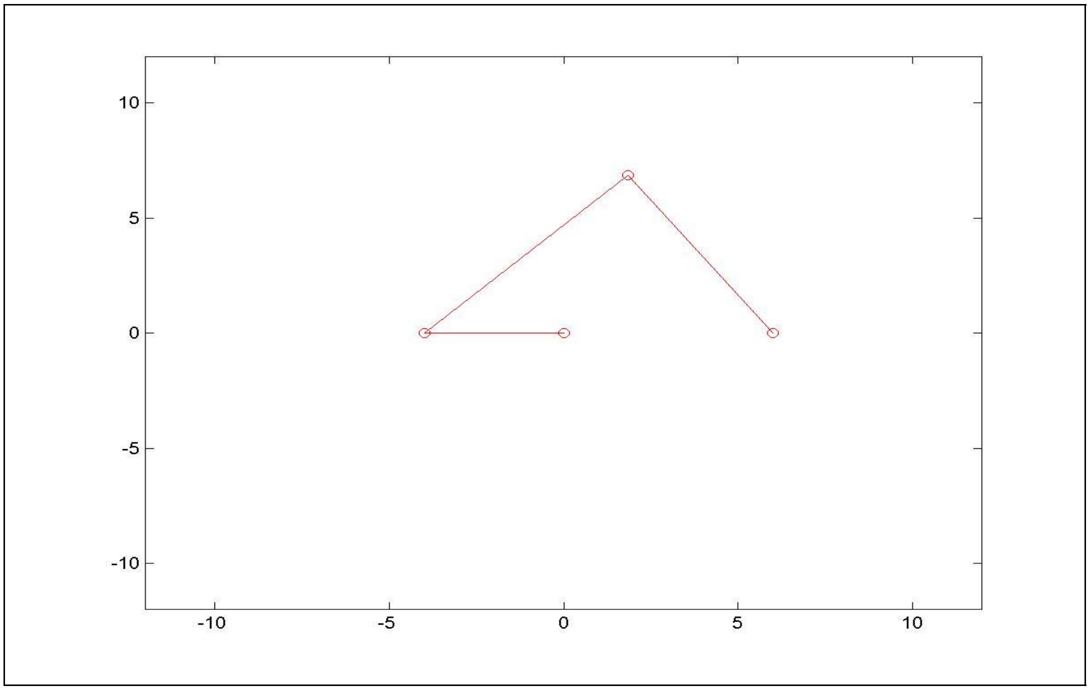


Figure 2-4. Graph generated using Matlab. Shown is the beginning of animation.

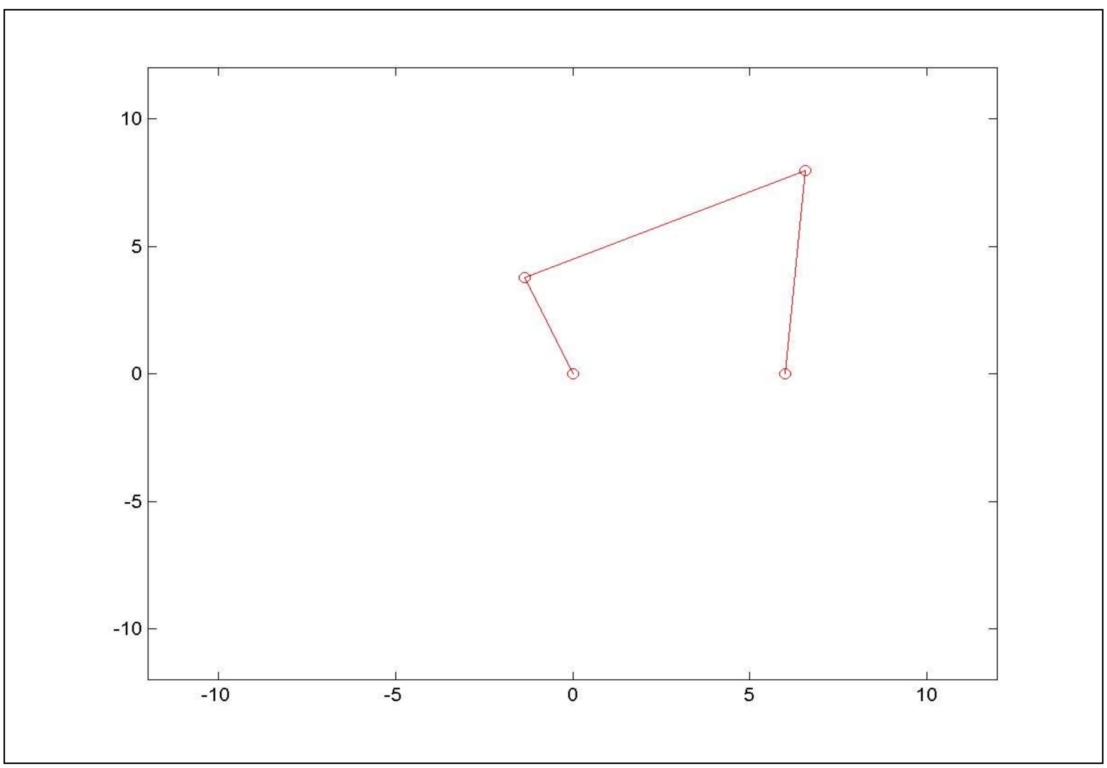


Figure 2-5. Graph showing the animation.

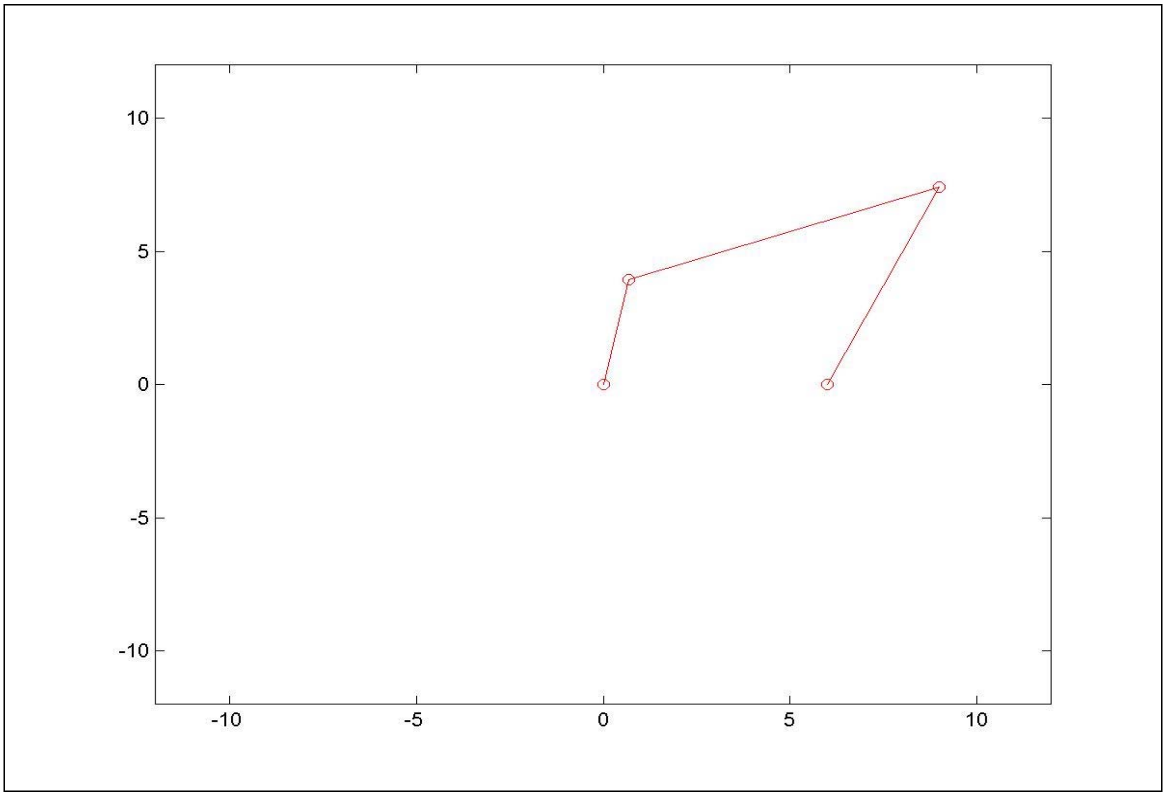


Figure 2-6. Graph showing the animation in progress.

During the initial phases of analysis, there was much interaction with the virtual prototyping group. After the preliminary model was chosen, it was given to the virtual prototyping group to animate in Adams. The two groups worked closely together to refine the model and analyze how the mechanism would perform.

After further modeling in Adams, the final model was chosen for manufacture. A detailed position, velocity, acceleration, and force analysis was performed on the model. This was a lengthy process and it used many concepts that were learned in class. The analysis would be performed with the point of interest being the point of release of the ball.

The position analysis was performed using the loop closure method (method III) and the graphical method. The loop closure equations were determined and using the mechanisms link lengths and angles, MATLAB was utilized to perform the calculations.

The velocity and acceleration analysis equations were obtained by differentiating the position equations once and twice, respectively. These equations were then put into MATLAB for calculation.

The force analysis equations were obtained using the free body diagram (FBD) method. Once these equations were determined, they were put into MATLAB for final calculation.

A detailed description of the step by step method in determining the equations is listed below:

1. Position Analysis

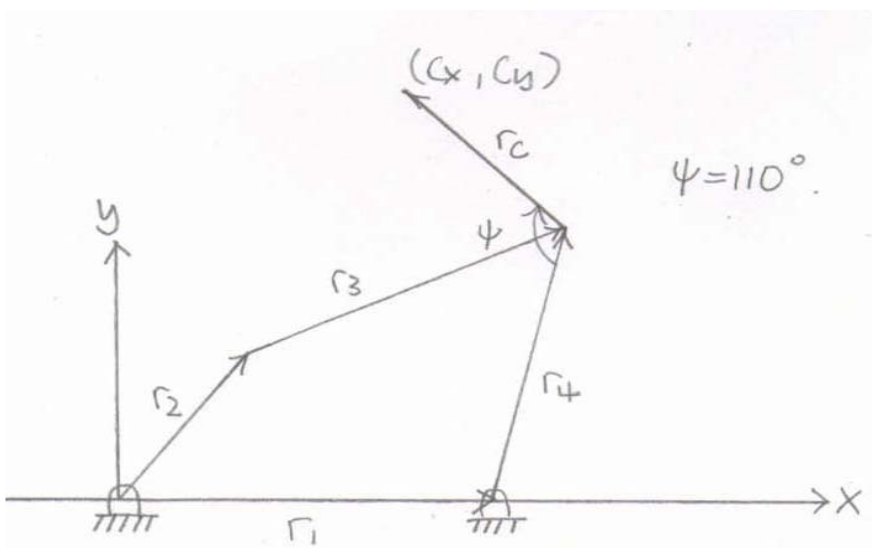


Figure 2-7. Nomenclature of four bars linkage.

By using loop closure equation,

$$r_1 \cos\theta_1 + r_4 \cos\theta_4 = r_2 \cos\theta_2 + r_3 \cos\theta_3$$
$$r_1 \sin\theta_1 + r_4 \sin\theta_4 = r_2 \sin\theta_2 + r_3 \sin\theta_3$$

Square both sides,

$$r_3^2\cos^2\theta_3 = r_1^2\cos^2\theta_1 + r_1\cos\theta_1 r_4\cos\theta_4 - r_1\cos\theta_1 r_2\cos\theta_2 + r_1\cos\theta_1 r_4\cos\theta_4 + r_4^2\cos^2\theta_4$$
$$- r_2\cos_2 r_4\cos\theta_4 - r_1\cos\theta_1 r_2\cos\theta_2 - r_2\cos\theta_2 r_4\cos\theta_4 + r_2^2\cos^2\theta_2$$

$$r_3^2\sin^2\theta_3 = r_1^2\sin^2\theta_1 + r_1\sin\theta_1 r_4\sin\theta_4 - r_1\sin\theta_1 r_2\sin\theta_2 + r_1\sin\theta_1 r_4\sin\theta_4 + r_4^2\sin^2\theta_4$$
$$- r_2\sin_2 r_4\sin\theta_4 - r_1\sin\theta_1 r_2\sin\theta_2 - r_2\sin\theta_2 r_4\sin\theta_4 + r_2^2\sin^2\theta_2$$

Using the substitution, $\sin^2+\cos^2=1$

$$r_3^2 = r_1^2 + r_2^2 + r_4^2 + 2r_1r_4(\cos\theta_1\cos\theta_4 + \sin\theta_1\sin\theta_4) - 2r_1r_2(\cos\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2)$$
$$- 2r_2r_4(\cos\theta_2\cos\theta_4 + \sin\theta_2\sin\theta_4)$$

Defining A, B, C as

$$A \equiv 2r_1r_4\cos\theta_1 - 2r_2r_4\cos\theta_2$$
$$B \equiv 2r_1r_4\sin\theta_1 - 2r_2r_4\sin\theta_2$$
$$C \equiv r_1^2 + r_2^2 + r_4^2 - r_3^2 - 2r_1r_2(\cos\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2)$$

Using the half angle substitutions,

$$\sin\theta_4 = \frac{2\tan\left(\theta_4/2\right)}{1+\tan^2\left(\theta_4/2\right)}$$

$$\cos\theta_4 = \frac{1-\tan^2\left(\theta_4/2\right)}{1+\tan^2\left(\theta_4/2\right)}$$

Substituting,

$$A\left[\frac{1-\tan^2\left(\theta_4/2\right)}{1+\tan^2\left(\theta_4/2\right)}\right] + B\left[\frac{2\tan\left(\theta_4/2\right)}{1+\tan^2\left(\theta_4/2\right)}\right] + C = 0$$

Defining

$$t \equiv \tan\left(\theta_4/2\right)$$

Simplifying

$$(C-A)t^2 + 2Bt + (A+C) = 0$$

Solving for t using the quadratic equation

$$t = \frac{-B \pm \sqrt{B^2 - C^2 + A^2}}{C-A}$$

$$\theta_4 = 2\tan^{-1} t$$

Now solving for theta 3 using the initial position equations

$$\theta_3 = \tan^{-1}\left[\frac{r_1 \sin\theta_1 + r_4 \sin\theta_4 - r_2 \sin\theta_2}{r_1 \cos\theta_1 + r_4 \cos\theta_4 - r_2 \cos\theta_2}\right]$$

The point of interest is the coupler point, r_c

$$\vec{r}_c = \vec{r}_2 + \vec{r}_5$$

In component form,

$$r_{cx} = r_2 \cos\theta_2 + r_5 \cos(\theta_3 + \psi_c)$$
$$r_{cy} = r_2 \sin\theta_2 + r_5 \sin(\theta_3 + \psi_c)$$

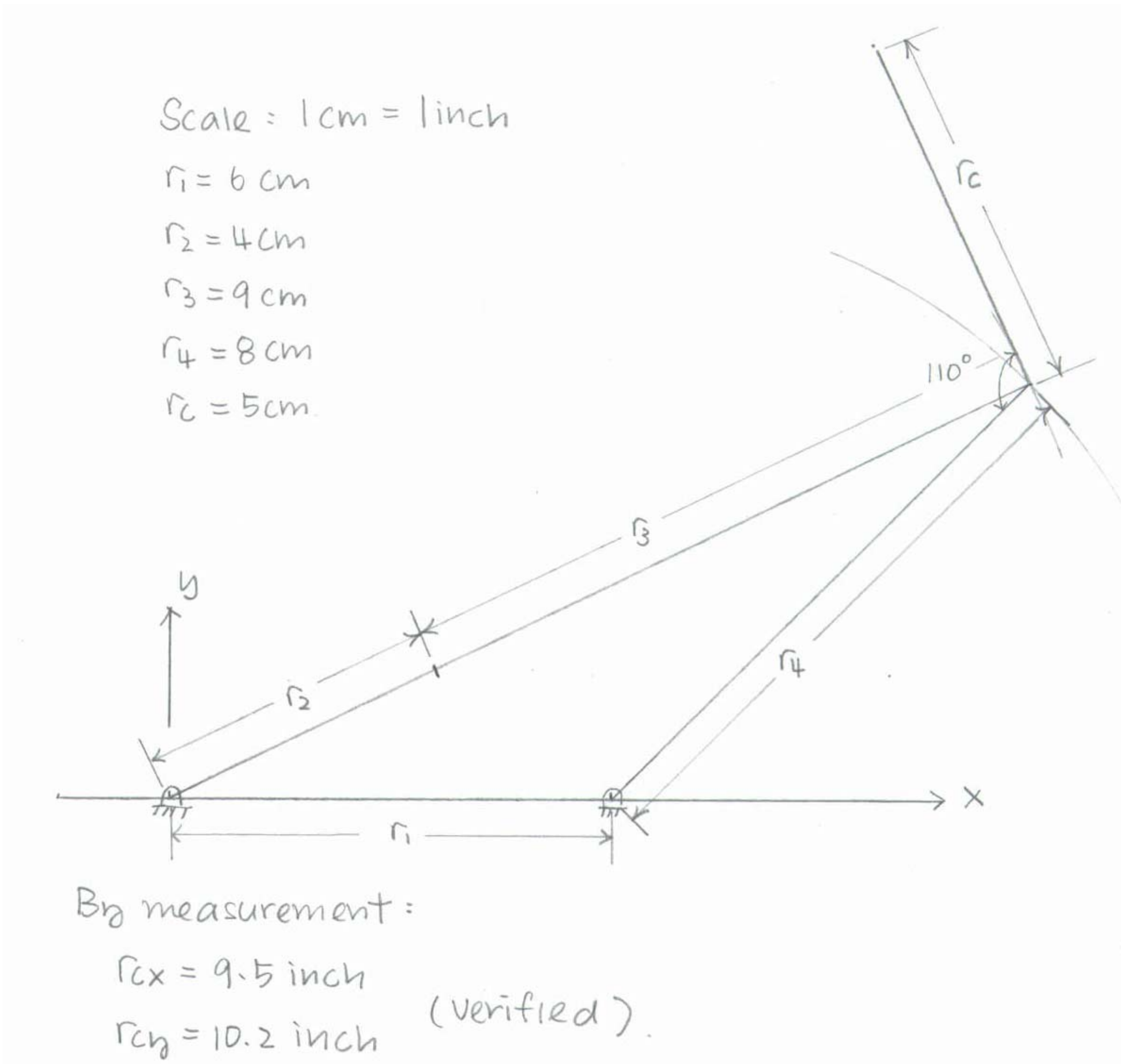
By using the MATLAB to calculate these equations,

$$r_{cx} = 9.6003 inch$$
$$r_{cy} = 10.1685 inch$$

Note: The MATLAB program file was shown in the Appendix part of this report.

Next, we use the following two methods to verify our answer.

1. Verify using Graphical Method:



2. Verify using Method II:

Let:

$$A_x = a\cos\theta_2$$
$$A_y = a\sin\theta_2$$
$$B_x = b\cos\theta_3$$
$$B_y = b\sin\theta_3$$
$$C_x = c\cos\theta_4$$
$$C_y = a\sin\theta_4$$
$$D_x = d\cos\theta_1$$
$$D_y = d\sin\theta_1$$

Using the method of circles and writing the equations,

$$b^2 = (B_x - A_x)^2 + (B_y - A_y)^2$$
$$c^2 = (B_x - D_x)^2 + (B_y - D_y)^2$$

Expanding terms,

$$b^2 = B_x^2 - 2A_xB_x + A_x^2 + B_y^2 - 2A_yB_y + A_y^2$$
$$c^2 = B_x^2 - 2B_xD_x + D_x^2 + B_y^2 - 2B_yD_y + D_y^2$$

Subtracting the above two equations and solving for B_x,

$$B_x = \frac{b^2 - c^2 - a^2 + d^2}{-2(A_x - D_x)} + \frac{A_y - D_y}{-A_x + D_x}B_y$$

Defining K_1 and K_2 as

$$K_1 = \frac{b^2 - c^2 - a^2 + d^2}{-2(A_x - D_x)}$$
$$K_2 = \frac{A_y - D_y}{-A_x + D_x}$$

And rewriting as

$$B_x = K_1 + K_2 B_y$$

Rewriting the expression for the second circle in terms of K_1 and K_2 as

$$c^2 = \left[K_1 + K_2 B_y - D_x\right]^2 + (B_y - D_y)^2$$

Defining K_3 as

$$K_3 = K_1 - D_x$$

$$c^2 = (K_3 + K_2 B_y)^2 + (B_y - D_y)^2$$

Expanding and collecting terms on B_x and B_y

$$B_y^2 (K_2^2 + 1) + B_y (2K_2 K_3 - D_y) + (K_3^2 + D_y^2 - c^2) = 0$$

Defining P, Q, and R as

$$P = (K_2^2 + 1)$$
$$Q = (2K_2 K_3 - D_y)$$
$$R = (K_3^2 + D_y^2 - c^2)$$

Then rewriting as

$$PB_y^2 + QB_y + R = 0$$

Using the quadratic equation to solve for B_y to obtain

$$B_y = \frac{-Q \pm \sqrt{Q^2 - 4PR}}{2P}$$

Once B_y has been found, B_x can be obtained by substituting back.

From B_x and B_y, θ_3 and θ_4 can be obtained from

$$\theta_3 = \tan^{-1}\left(\frac{B_y - A_y}{B_x - A_x}\right)$$
$$\theta_4 = \tan^{-1}\left(\frac{B_y}{B_x - d}\right)$$

Using these angles the position of the point of interest can be found from

$$r_{cx} = B_x - r_5 \cos\theta_5$$
$$r_{cy} = B_y + r_5 \sin\theta_5$$

The result was found by using Matlab program, which gave us answer:

$$r_{cx} = 9.6003 inch \qquad \textit{(Verified)}$$
$$r_{cy} = 10.1685 inch$$

2. Velocity Analysis

Starting with the loop closure equations,

$$r_1 \cos\theta_1 + r_4 \cos\theta_4 = r_2 \cos\theta_2 + r_3 \cos\theta_3$$
$$r_1 \sin\theta_1 + r_4 \sin\theta_4 = r_2 \sin\theta_2 + r_3 \sin\theta_3$$

Differentiating,

$$-r_1 \sin\theta_1\dot{\theta}_1 - r_4 \sin\theta_4\dot{\theta}_4 = -r_2 \sin\theta_2\dot{\theta}_2 - r_3 \sin\theta_3\dot{\theta}_3$$
$$r_1 \cos\theta_1\dot{\theta}_1 + r_4 \cos\theta_4\dot{\theta}_4 = r_2 \cos\theta_2\dot{\theta}_2 + r_3 \cos\theta_3\dot{\theta}_3$$

Noting that theta 1 is the ground link and that theta 1 dot is zero,

$$-r_3 \sin\theta_3\dot{\theta}_3 + r_4 \sin\theta_4\dot{\theta}_4 = r_2 \sin\theta_2\dot{\theta}_2$$
$$-r_3 \cos\theta_3\dot{\theta}_3 + r_4 \cos\theta_4\dot{\theta}_4 = r_2 \cos\theta_2\dot{\theta}_2$$

Putting into matrix form

$$\begin{bmatrix} -r_3 \sin\theta_3 & r_4 \sin\theta_4 \\ -r_3 \sin\theta_3 & r_4 \sin\theta_4 \end{bmatrix} \begin{bmatrix} \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} = \begin{bmatrix} r_2 \sin\theta_2\dot{\theta}_2 \\ r_2 \cos\theta_2\dot{\theta}_2 \end{bmatrix}$$

Solving for theta 3 dot and theta 4 dot,

$$\begin{bmatrix} \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} = \begin{bmatrix} -r_3 \sin\theta_3 & r_4 \sin\theta_4 \\ -r_3 \sin\theta_3 & r_4 \sin\theta_4 \end{bmatrix}^{-1} \begin{bmatrix} r_2 \sin\theta_2\dot{\theta}_2 \\ r_2 \cos\theta_2\dot{\theta}_2 \end{bmatrix}$$

Now for the coupler which is the point of interest,

$$\vec{r}_c = \vec{r}_2 + \vec{r}_5$$
$$\vec{r}_c = \left(r_2 \cos\theta_2 + r_5 \cos(\theta_3 + \psi_c)\right)\hat{i} + \left(r_2 \sin\theta_2 + r_5 \sin(\theta_3 + \psi_c)\right)\hat{j}$$

Differentiating,

$$\dot{\vec{r}}_c = \left(-r_2 \sin\theta_2\dot{\theta}_2 - r_5 \sin(\theta_3 + \psi_c)\dot{\theta}_3\right)\hat{i} + \left(r_2 \cos\theta_2\dot{\theta}_2 + r_5 \cos(\theta_3 + \psi_c)\dot{\theta}_3\right)\hat{j}$$

Putting into matrix form

$$\begin{bmatrix} \dot{r}_{cx} \\ \dot{r}_{cy} \end{bmatrix} = \begin{bmatrix} -r_2 \sin\theta_2 & -r_5 \sin(\theta_3 + \psi_c) \\ r_2 \cos\theta_2 & r_5 \cos(\theta_3 + \psi_c) \end{bmatrix} \begin{bmatrix} \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix}$$

By using the MATLAB, we wrote a program to calculate the answer. The answers are:

$$\dot{r}_{cx} = 8.075 rad/s$$
$$\dot{r}_{cy} = --2.8591 rad/s$$

Note: The MATLAB program was included in the Appendix for reference.

3. Acceleration Analysis

Beginning with the Velocity equations,

$$-r_1 \sin\theta_1\dot{\theta}_1 - r_4 \sin\theta_4\dot{\theta}_4 = -r_2 \sin\theta_2\dot{\theta}_2 - r_3 \sin\theta_3\dot{\theta}_3$$
$$r_1 \cos\theta_1\dot{\theta}_1 + r_4 \cos\theta_4\dot{\theta}_4 = r_2 \cos\theta_2\dot{\theta}_2 + r_3 \cos\theta_3\dot{\theta}_3$$

And differentiating again,

$$-r_1 \sin\theta_1\ddot{\theta}_1 - r_1 \cos\theta_1\dot{\theta}_1^2 - r_4 \sin\theta_4\ddot{\theta}_4 - r_4 \cos\theta_4\dot{\theta}_4^2 = -r_2 \sin\theta_2\ddot{\theta}_2 - r_2 \cos\theta_1\dot{\theta}_1^2 - r_3 \sin\theta_3\ddot{\theta}_3 - r_3 \cos\theta_3\dot{\theta}_3^2$$
$$r_1 \cos\theta_1\ddot{\theta}_1 - r_1 \sin\theta_1\dot{\theta}_1^2 + r_4 \cos\theta_4\ddot{\theta}_4 - r_4 \sin\theta_4\dot{\theta}_4^2 = r_2 \cos\theta_2\ddot{\theta}_2 - r_2 \sin\theta_1\dot{\theta}_1^2 + r_3 \cos\theta_3\ddot{\theta}_3 - r_3 \sin\theta_3\dot{\theta}_3^2$$

Putting into matrix form, and noting that theta 1 double dot is zero, and theta 1 is zero,

$$\begin{bmatrix} -r\sin\theta_3 & r_4 \sin\theta_4 \\ -r_3 \cos\theta_3 & r_4 \cos\theta_4 \end{bmatrix} \begin{bmatrix} \ddot{\theta}_3 \\ \ddot{\theta}_4 \end{bmatrix} = \begin{bmatrix} -r_4 \cos\theta_4\dot{\theta}_4^2 + r_2 \sin\theta_2\ddot{\theta}_2 + r_2 \cos\theta_1\dot{\theta}_1^2 + r_3 \cos\theta_3\dot{\theta}_3 \\ r_4 \sin\theta_4\dot{\theta}_4^2 + r_2 \cos\theta_2\ddot{\theta}_2 - r_2 \sin\theta_1\dot{\theta}_1^2 - r_3 \sin\theta_3\dot{\theta}_3^2 \end{bmatrix}$$

Solving for theta 3 double dot and theta 4 double dot

$$\begin{bmatrix} \ddot{\theta}_3 \\ \ddot{\theta}_4 \end{bmatrix} = \begin{bmatrix} -r\sin\theta_3 & r_4 \sin\theta_4 \\ -r_3 \cos\theta_3 & r_4 \cos\theta_4 \end{bmatrix}^{-1} \begin{bmatrix} -r_4 \cos\theta_4\dot{\theta}_4^2 + r_2 \sin\theta_2\ddot{\theta}_2 + r_2 \cos\theta_1\dot{\theta}_1^2 + r_3 \cos\theta_3\dot{\theta}_3 \\ r_4 \sin\theta_4\dot{\theta}_4^2 + r_2 \cos\theta_2\ddot{\theta}_2 - r_2 \sin\theta_1\dot{\theta}_1^2 - r_3 \sin\theta_3\dot{\theta}_3^2 \end{bmatrix}$$

For the coupler point

$$\dot{\vec{r}}_c = \left(-r_2 \sin\theta_2\dot{\theta}_2 - r_5 \sin(\theta_3 + \psi_c)\dot{\theta}_3\right)\hat{i} + \left(r_2 \cos\theta_2\dot{\theta}_2 + r_5 \cos(\theta_3 + \psi_c)\dot{\theta}_3\right)\hat{j}$$

Input these formulas into MATLAB, the answer found to be:

$$\ddot{r}_{cx} = -304.088 rad/s^2$$
$$\ddot{r}_{cy} = 105.2477 rad/s^2$$

Note: The MATLAB program was included in the Appendix for reference.

4. Force Analysis

(Noting that $F_{32} = -F_{23}$, $F_{43} = -F_{34}$ and substituting into the equations)

The following steps were done using the free body diagram method.

<u>Link 2:</u>

$$F_{12x} - m_2\ddot{x}_{G2} - F_{23x} = 0$$

$$F_{12y} - m_2\ddot{y}_{G2} - m_2 g - F_{23y} = 0$$

$$F_{12x}a_2 \sin\theta_2 - F_{12y}a_2 \cos\theta_2 + F_{23x}b_2 \sin\theta_2 - F_{23y}b_2 \cos\theta_2 + \tau = I_2\ddot{\theta}_2$$

<u>Link 3:</u>

$$F_{23x} - m_3\ddot{x}_{G3} - F_{43x} + F_s = 0$$

$$F_{23y} - m_3\ddot{y}_{G3} - m_3 g - F_{34y} = 0$$

$$F_{23x}a_3 \sin\theta_3 - F_{23y}a_3 \cos\theta_3 + F_{34x}b_2 \sin\theta_3 - F_{34y}b_2 \cos\theta_3 + \tau = I_3\ddot{\theta}_3$$

<u>Link 4:</u>

$$F_{34x} - m_4\ddot{x}_{G4} - F_{14x} + F_s = 0$$

$$F_{34y} - m_4\ddot{y}_{G4} - m_4 g + F_{14y} = 0$$

$$F_{34x}a_4 \sin\theta_4 - F_{34y}a_4 \cos\theta_4 + F_{14x}b_4 \sin\theta_4 - F_{14y}b_4 \cos\theta_4 + \tau = I_4\ddot{\theta}_4$$

Putting in Matrix form:

$$A = \begin{bmatrix} 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ a_2 s_2 & -a_2 c_2 & b_2 s_2 & -b_2 s_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & a_2 s_2 & -a_2 c_2 & b_2 s_2 & -b_2 s_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & a_4 s_4 & -a_4 c_4 & b_4 s_4 & -b_4 s_4 & 0 \end{bmatrix}$$

$$b = \begin{bmatrix} m_2 \ddot{x}_{G2} \\ m_2 (y_{G2} + g) \\ I_2 \ddot{\theta}_2 \\ m_3 \ddot{x}_{G3} - F_s \\ m_3 (\ddot{y}_{G3} + g) \\ I_3 \ddot{\theta}_3 \\ m_4 \ddot{x}_{G4} - F_s \\ m_4 (\ddot{y}_{G4} + g) \\ I_4 \ddot{\theta}_4 \end{bmatrix} \qquad \bar{x} = \begin{bmatrix} F_{12x} \\ F_{12y} \\ F_{23x} \\ F_{23y} \\ F_{34x} \\ F_{34y} \\ F_{12x} \\ F_{12y} \\ \tau \end{bmatrix}$$

$$A \cdot \bar{x} = b$$

Solving for the forces by using:

$$\bar{x} = A^{-1} \cdot b$$

We solved the matrix by using the Matlab program. The Matlab program was included in the appendix. The answer was shown in the next page.

Note: F12x means force on link 1 from link2 in the x direction
Force is in units of pound-force
Torque is in units of inch-pounds

Answer:

F12x = -7.5799
F12y = -2.4500
F23x = -7.5070
F23y = -2.8550
F34x = -5.7614
F34y = -4.2697
F14x = 4.1723
F14y = 5.5584

Torque on input link = 0.3519 lb-inch= 5.6304 once-inch.

Note: From this result, we can see that the torque that the motor can produce is more than enough to provide the power to drive the links. The motor has a maximum torque of 75 once-inch. This result gives us a wide range of selecting the elastic band that we are going to use. This will be determining by the manufacturing group experimentally.

3. Virtual Prototype Process.

Our goal is to simulate the model of our design and place a ball on the model to model the result of our design. Our group strategy is to fully utilize the advantage of Virtual Prototype tools such as ADAMS and MATLAB to virtualize and analyzed our model before we actually build it. We have the basic model that comes from the analysis group. Now our job is to use our available tools to choose our best-designed mechanism. The main task that we will deal with is the optimization for our mechanism.

Since there are a lot of design variables, such as the link length, the angle, the length of the elastic band that we are going to compress or elongate. Due to this complex of variable, we have set the following step in our process of model our design.

Optimization Process:

1. To minimize the variable that we need to consider, we set our input link = 4 inch, output link=8 inch, ground link=6 inch and set the coupler link as the variable. By doing this we are able to use a MATLAB program to choose the length for the coupler. The program of the MATLAB was given in the Appendix part. This part of work is work together with the Analysis group. And the comparison of each model was given in the analysis part.

2. We found that from the analysis, when the length of the coupler link increased, the limiting angle (maximum and minimum angle) that the output link can move become smaller. So, we found that it is better to specify the range that we need to pull the elastic band and find out how much range we want to pull the elastic band. Then determine the length of the coupler.

3. Then we start using the ADAMS to simulate our model. Here we choose to optimize the initial height for the ball to release that is the highest the initial height the farthest the distance we can shoot the ball with a same initial conditions. We also choose to optimize the initial angle that we are going to release the ball. 45 degree will be our optimized angle.

First Week Progress:

a. In the first week, we start trying using ADAMS to create some simple model and try to familiarize each function that ADAMS provided.

b. We get some idea from the analysis group that what our model will base on. So we create the model and run it using ADAMS and find the angle and position change for different model.

c. We have encountered some problem when we input the motion to the model. Because we do not really know the actual torque that the motor can provide, we just use the motion function (which is 30rpm) in ADAMS and run the model.

d. Figure 1-1 shows the model that we have creates using ADAMS. This model will place the ball holder at the longest link and shoot the ball in the negative x-direction. This model also used a compressible spring to store the energy and this energy will be use to shoot the ball.

e. The measurement that we made is located at the ball holder. That is the x-direction displacement, y-direction displacement, angular velocity, and angular acceleration. This ADAMS function gives us some brief idea how the model going to be and how is the change in position and acceleration of our point of interest.

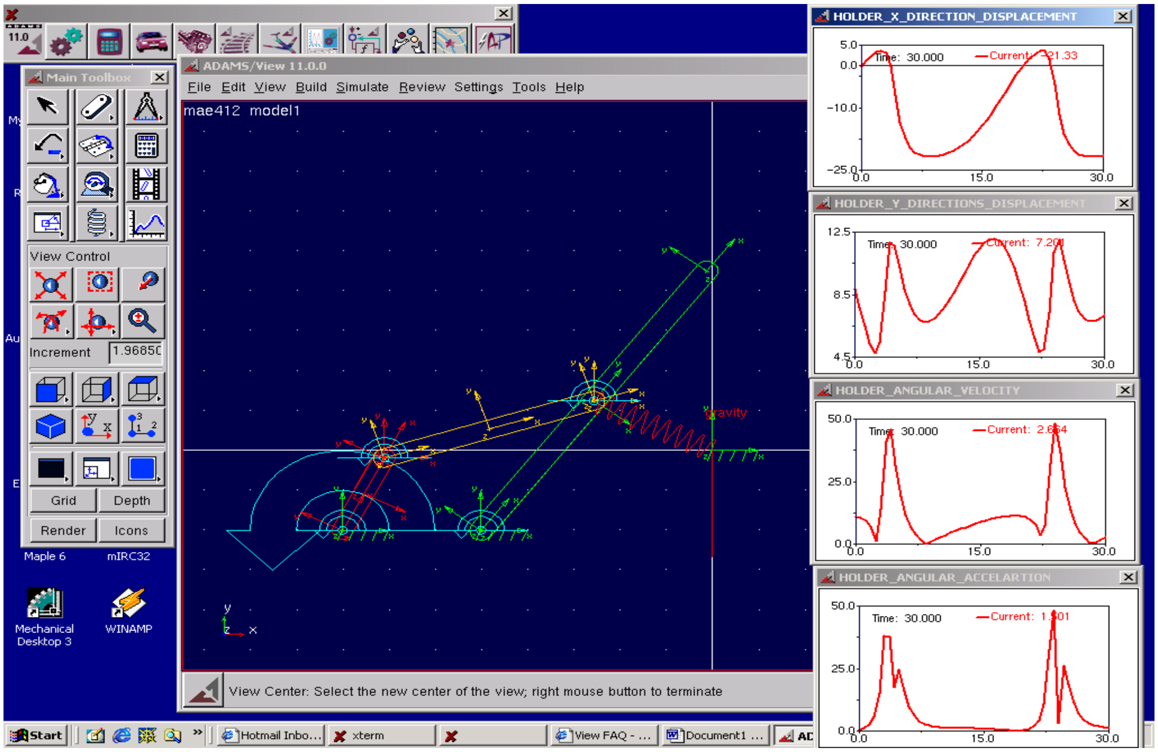


Figure 3-1. Model simulated using ADAMS with the measure of the displacement, angular velocity, x-direction and y-direction displacement.

f. From our analysis, this model has a maximum acceleration when the spring is fully compressed. However, if we use the compression of the spring, we must also consider the buckling problem of the spring. In this case, we decided to elongate the spring instead of compress it.

g. The problem that we encounter in this stage is the length of the links that we are going to use here. This required us to fulfill the requirement of the constraint. Another problem is that we did not know the density of the ball. The torque unit and the mass init that used in the ADAMS also confusing us.

Second week Progress:

We have find out the information for the all the things that we needed to draw the model. The following is what we have done for the optimization process.

1. We have decided to fix some of the variables. The variable that we have fixed is the ground link, which is 6 inches, input links, which is 4 inches, and the output link, which is 8 inches. We did this by trail an error on a 2 ft by 2 ft constraints. So the only variable that left here is the R_3 links. From the formula that we have derived for R_3 shows that when the value of R_3 increase, the angle that the output links can move actually decreased. This give us some clue on how should we change the value of R_3. If we want to pull the elastic band for a larger distance to store more energy for the ball, we should increase the length of R_3 (the coupler).

2. However, to maintain a Grashof condition, which is S+L = P+Q, we should give a value of R3 between 8-9 inches. This result has greatly decreased the variable that we have faced. The drawback for doing this is that the result may not give us an optimized result that we want.

3. Due to this reason, we need to do some analysis base on our requirement. We develop a MATLAB program that gives us the angle between the input links and the output link. This part is basically done with the help of Analysis group. The program is attached in the Appendix part of this report. From the program we have choose the below two configuration of coupler that match our requirements.

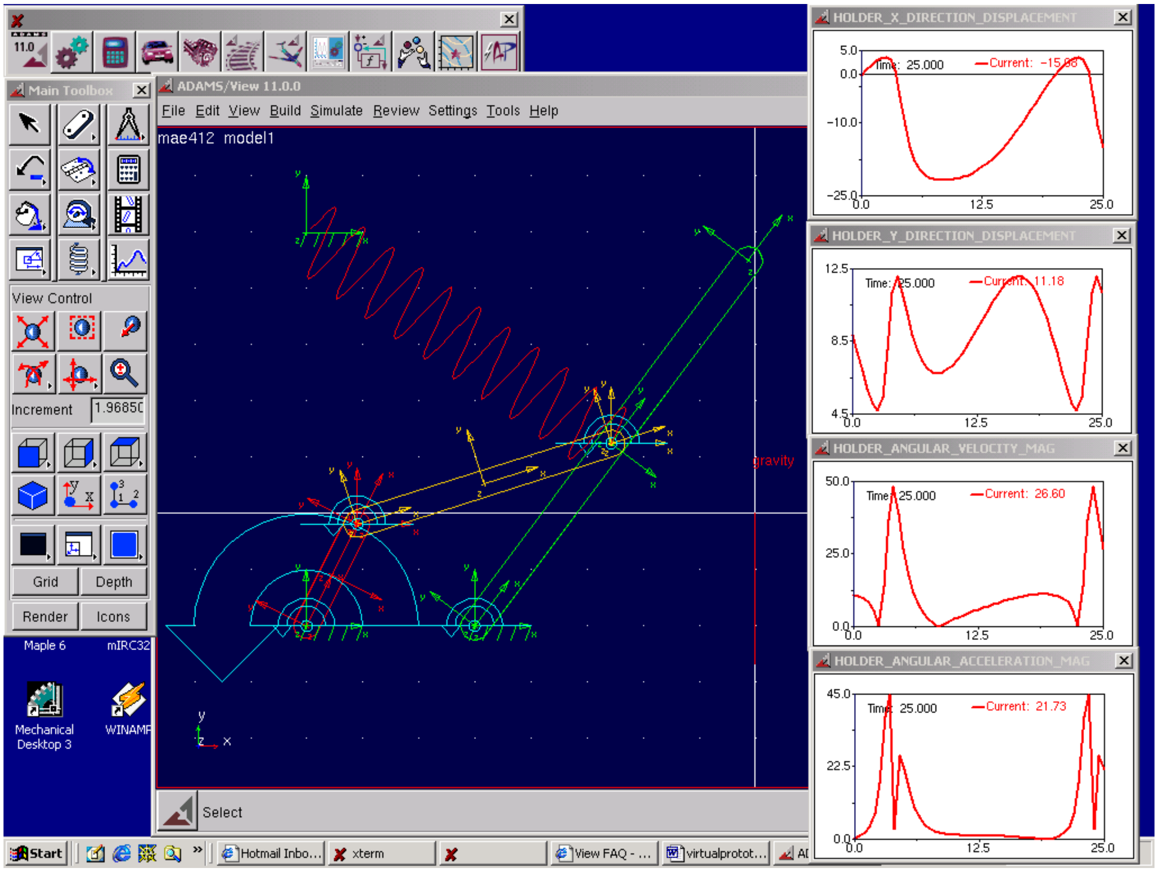


Figure 3-2. Model change for elongate the spring instead of compress the spring.

4. We have found the following two configurations that are possible for our design. This is shown in Table 1.

Coupler choices	Output links				Input link			Base height
	Output max. Angle	Output min. angle	Range covered	Full Length	Min input angle	Max input angle	Range covered	
9 inch	38.625°	135.95°	97.32°	16	-94.86°	154.67°	249.33°	7.5 inch
8 inch	28.955°	117.279°	88.32°	18	-75.52°	143.66°	219.19°	5.5 inch

5. The choice of each is competitive. If we choose the coupler of 9 inches, we could have the following advantage:

   a. We have a greater out put range; this means if we put an elastic band in front of our output link, we can elongate the elastic band longer than the 8-inch configuration. This will give us more energy stored.
   b. Furthermore, we do not have to make the output link too long because this may in turn increase the weight of the structure, which is what we need to minimize.

The only disadvantage is that we need to build our base at a higher place. This May cause the structure located at a higher place. The stability of the structure has to be considering here.

6. If we choose the 8 inch configuration, we will have the following advantage:
   a. The minimum angle the input links and the output link are now at a smaller angle. This gives us an advantage if we want to shoot the ball at a 45° angle.
   b. Furthermore, this configuration will allow us to build the base at a height of 5.5 inches.
   c. The obvious disadvantage is the range of the output links travel is now has a smaller range. This makes it impossible to pull the elastic band for long range.

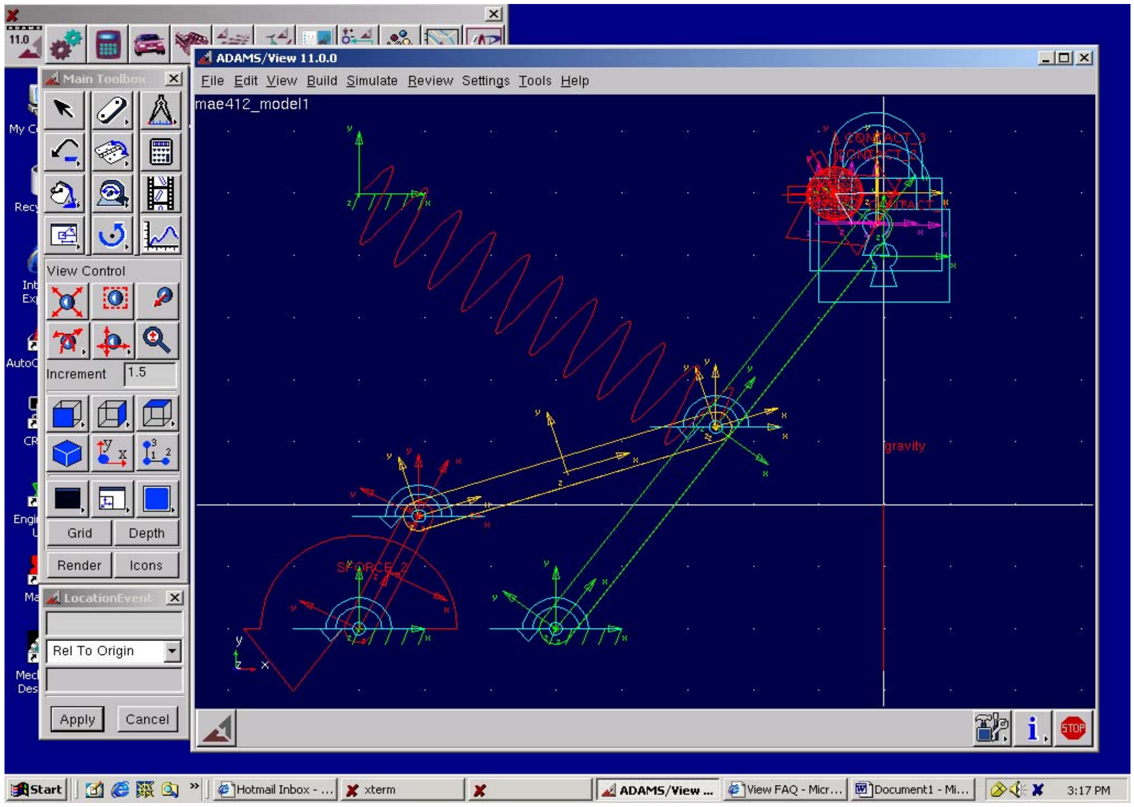


Figure 3-3. Model with a ball located on the ball holder.

Note for Figure 3-3: in this figure, the two "lock shape" figure represents a fix joint on the link. This is to create a ball holder, one fix joint connect the two ball holder and one fix joint connect the ball holder to the link. To place a ball on the ball holder, we need to create a force between the ball and the surface that the ball laid. The contact force needed in Adams is "sphere to plane" force contact. In this case, two such forces are created.

7. After we discuss this issue with the manufacture group, they suggested us to choose the second configuration because we want to optimize the initial angle at 45°. This configuration will also give the output links more places to accelerate. To overcome the problem of pulling the elastic band at smaller range, they also suggest that we could instead use an elastic band with a larger stiffness.

8. We have calculate all the data and they are shown bellow:

Table 3-1. Specification of each links

Links	Length	Diameter	Thickness	Materials
Input	4 inch	0.5 inch	0.0625 inch	Wood
Output	8 inch	0.4 inch	0.0625 inch	Wood
Couplerx2	9 inch	0.3 inch	0.0625 inch	Wood

Table 3-2. Specification of Squash ball.

Items	Diameter	Mass	Density
Ball	1.7 inch	24 +/- 1 gram	3.369×10^{-3} lbf/m^3

Table 3-3. Specification of ball holder.

Items	Length	Width	Thickness	Material
Ball holder	2 inch	2 inch	0.0625 inch	Wood

9. These data were input to the ADAMS program to see how the links moves. The solution was shown in the following Figure 1-4. It shows us that the ball actually shoot out with this simple configuration of linkage. This gives us confidence in the choice of our model. Base on the analysis using ADAMS, we know that our model will work.

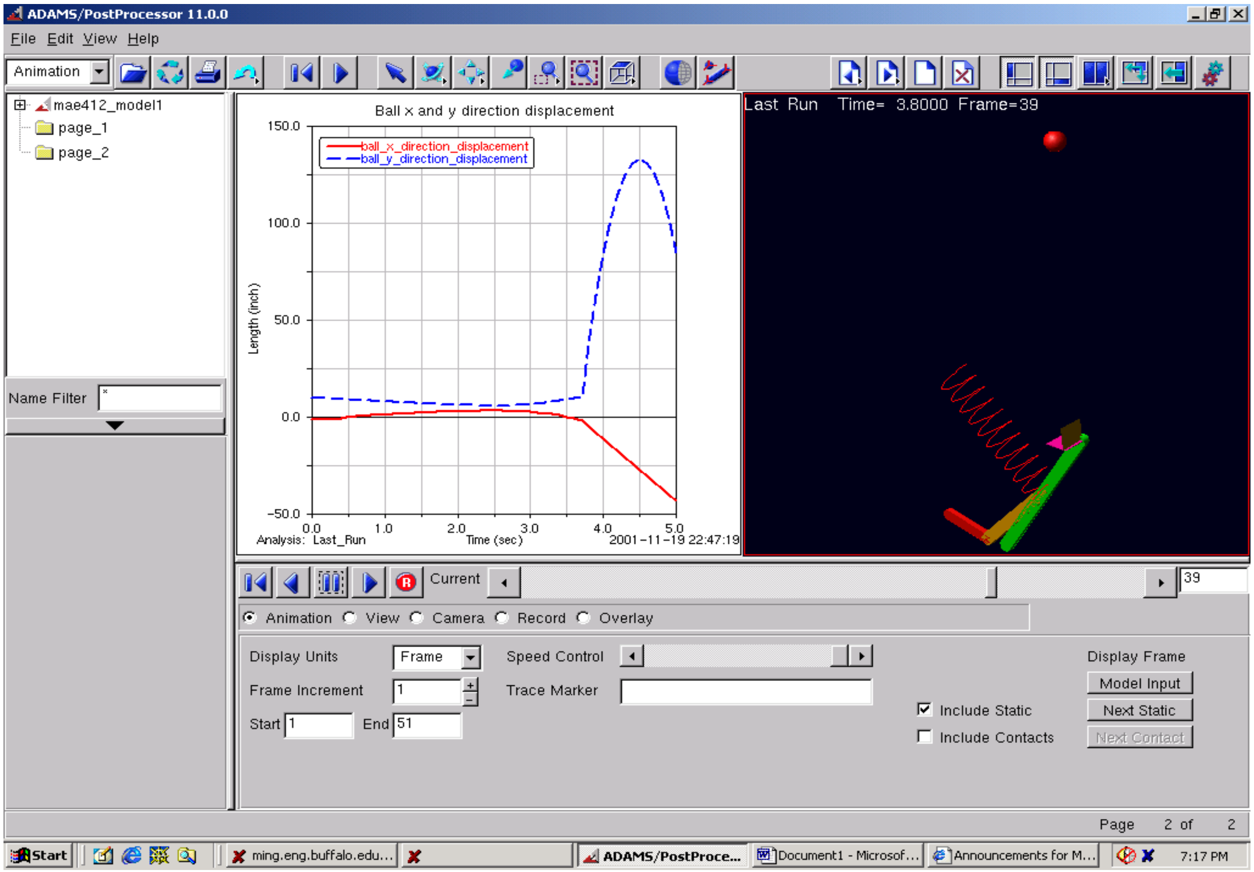


Figure 3-4. Analysis and graph showing the ball launching. The plot beside the animation of the model shows the y and x direction displacement of the ball.

Figure 3-4 shows the graph that we use in analysis our data. This can be found in the PostProcessor function under that ADAMS. In this graph, it shows the x direction and y direction displacement of the ball. This is done by placing a marker on the ball and creates the measurement that we want. The y direction displacement shows that the ball was shooting at a nearly vertical direction and it shoot to a high of nearly 130 inch. Which is around 10.8 ft. This is a satisfactory distance. From here, we have an idea that at least the ball will have an initial velocity that can shoot it to that height. Next, we examined the x and y direction velocity using ADAMS. On the right hand side of Figure 1-4 is the model view with the ball actually release from the ball holder.

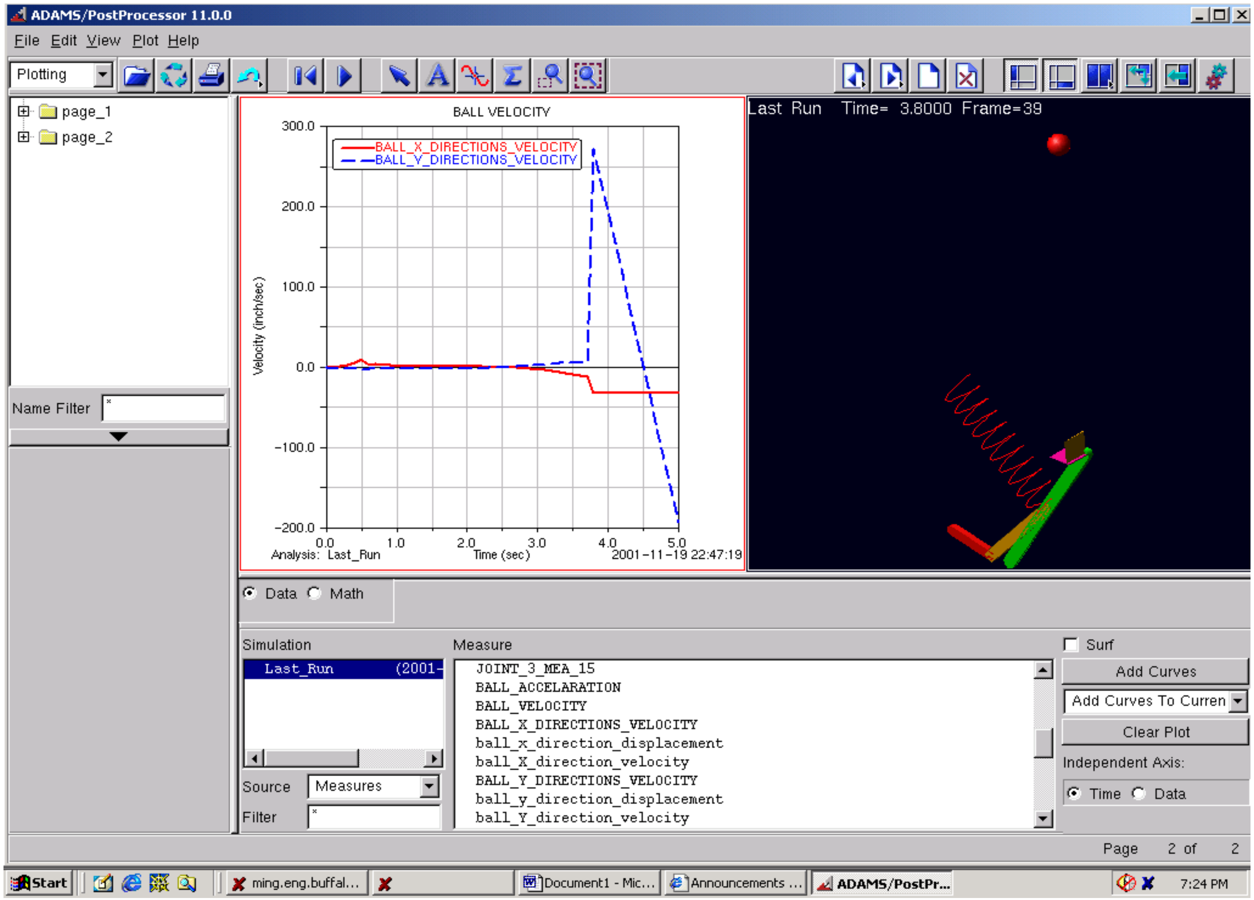


Figure 3-5. Sample graph of doing our analysis using Adams. This graph shows that the change in the velocity in both y and x direction. This was done by placing a measure marker on the ball and measured the velocity changes with respect to time.

Figure 3-5 shows that the ball holder launched the ball. It can be seen from the graph that at that instance, the initial y direction velocity have a value of around 250 inch/s. after it reach its maximum height, the ball drop because of the gravity force. From this analysis, we can estimate that our ball will have an approximate initial velocity of 250 inch/s. If we could made the model such that the ball launch at a 45-degree angle, the maximum distance can be obtain. This part of work was left to the Manufacture group.

Our analysis using ADAMS was done quite successfully. It gave us an idea that our model will work and give us some brief idea how far the ball will go. The function in ADAMS such as parameterized the links allowed us to change the length of the links and see what is the effect of the change to the model. We have chosen the first configuration and give our modeling and all the specification to the manufacturing group.

Third week Progress:

This week, after the manufacturing group has built the model, we see the different between the actual model and the one that we have drawn. The main different is the base that they have build is not a flat base but in turn is a triangular which can greatly increase the stability of the system. We could not draw this part of the structure and instead this is not necessary. This is because the base actually is not the part they we are going to analyze. However, since they change the link to a cylinder one instead of a flat link that we have designed, we need to change our model in ADAMS so that the result that gives in ADAMS will not be too far from our actual model. We thus change the links to all cylindrical links, with a ball holder. This is shown in Figure 3-4.

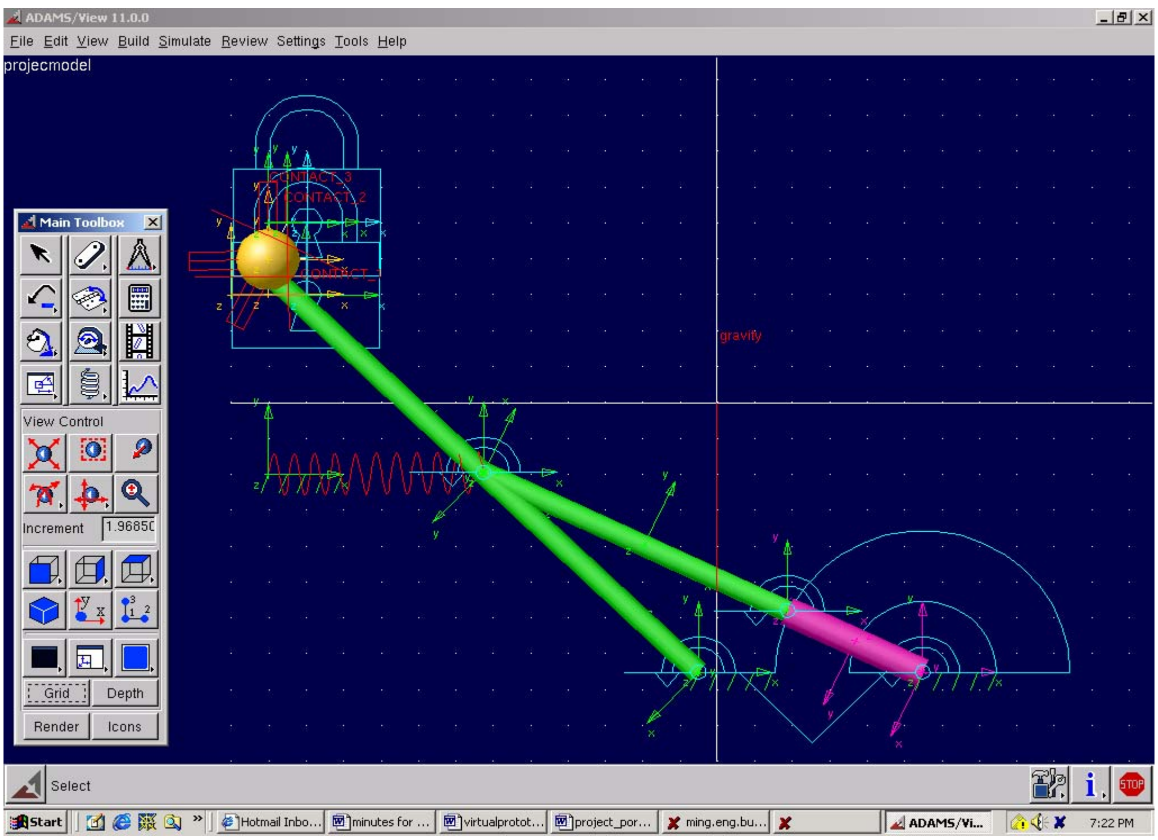


Figure 3-6. Front view of modified model.

Figure 3-6. The Front View of the four bar linkage in our model. The ball is attached to the ball holder and the spring is attached to the ground. In this model, the pink color links is the input link. The output link is attached with a ball on the ball holder. The coupler is 9 inches in this case. The only different between the actual four bar mechanism and this model is that in the actual model, we actually used two parallel couplers. This is because the force that the coupler experience is mainly the tension force. This is to increase the structure stability of our model, as suggested by the manufacturing group.

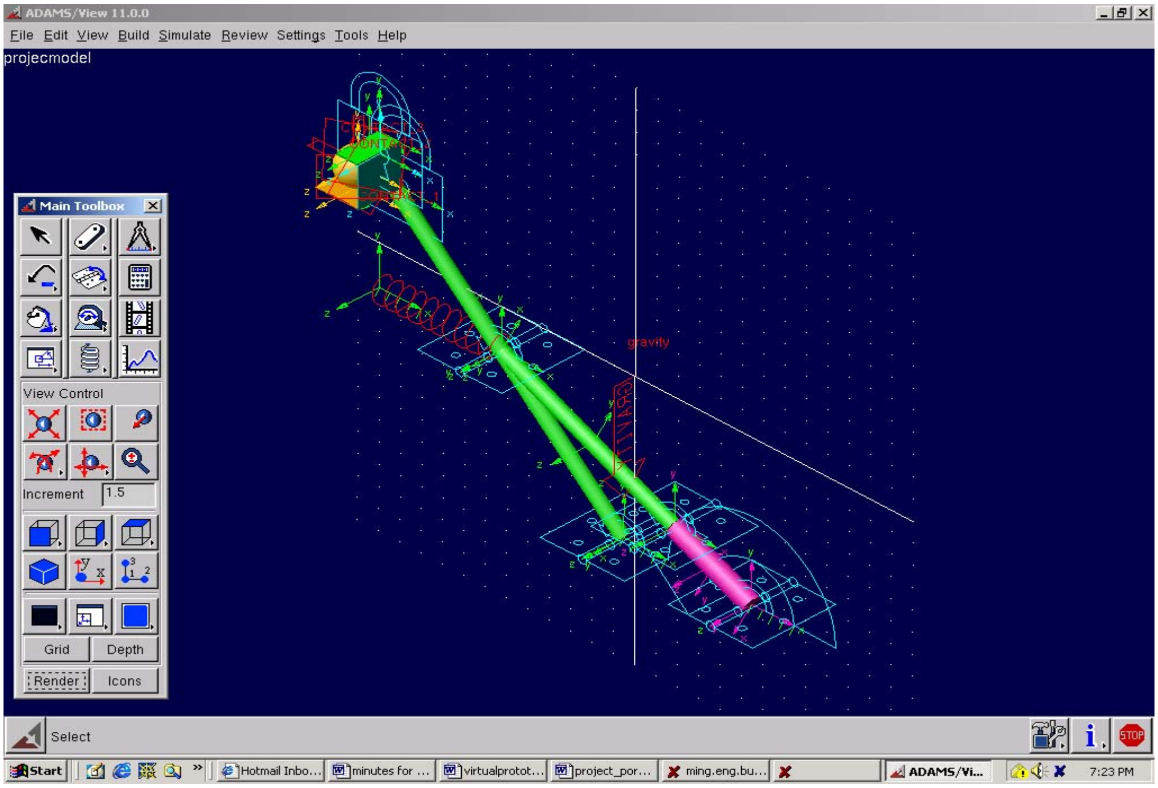


Figure 3-7. This graph shows the oblige view of the system. From this view, we can clearly see the ball is located at the ball holder.

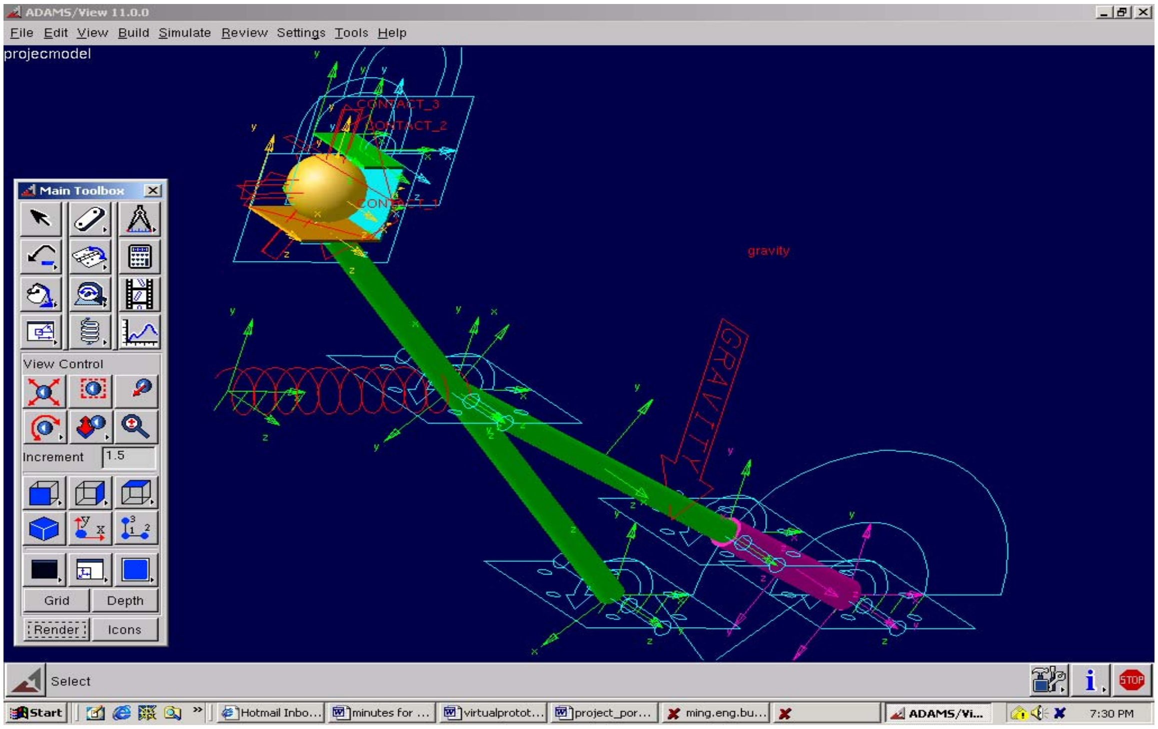


Figure 3-8. Figure that shows the model from another view. The four bar mechanism and the ball with a ball holder is shown clearly in the figure. From this graph, we can also see that the gravity force in acting in the negative y direction.

The changes that the manufacture group did are on the base structure and the design of the follower. After we have the dimensions of the structure that we use in for our model, we draw the model using AutoCAD and Pro-Engineering Software to draw our model. These were shown in the following page.

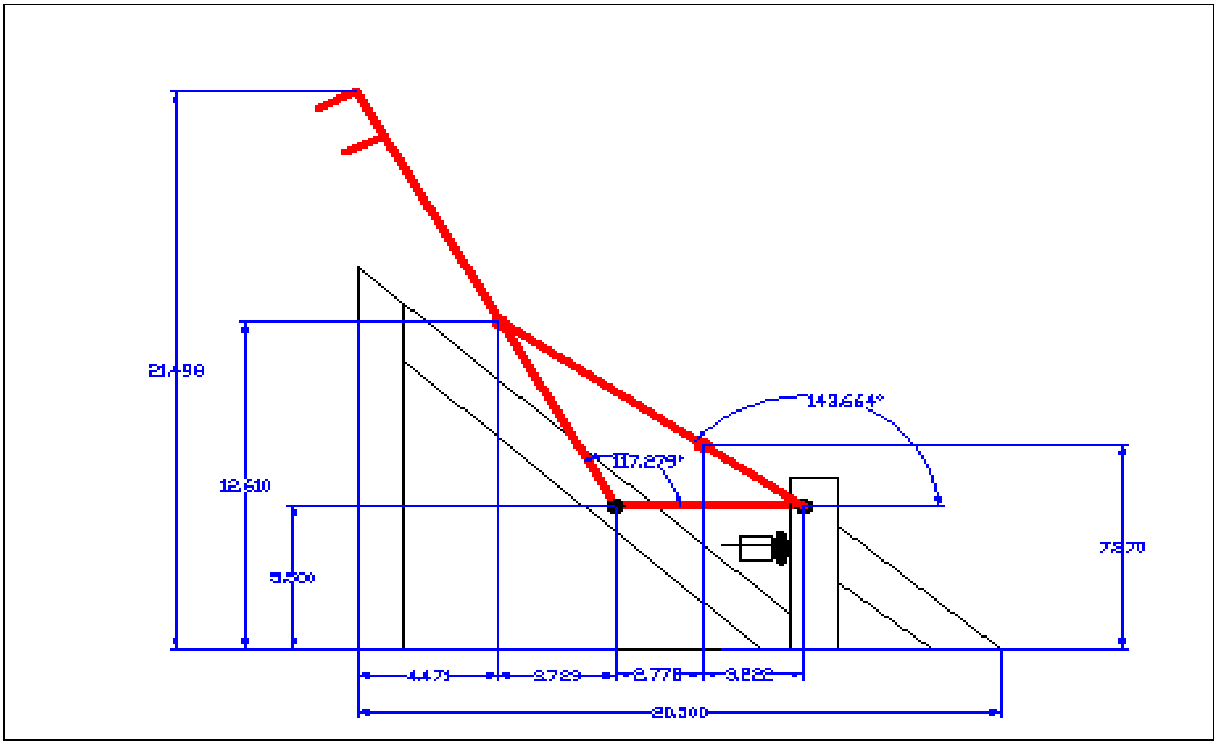


Figure 3-9. Graph showing the starting point of our mechanism.

Figure 3-9 shows a 4 bar mechanism in starting point. The maximum input angle is 143.664° and the maximum output angle is 117.279°. Bar 1, R1 is 6.5 in; bar 2, R2 is 4 in; bar 3 R3 is 8 in and bar 4 R4 is 8 in.

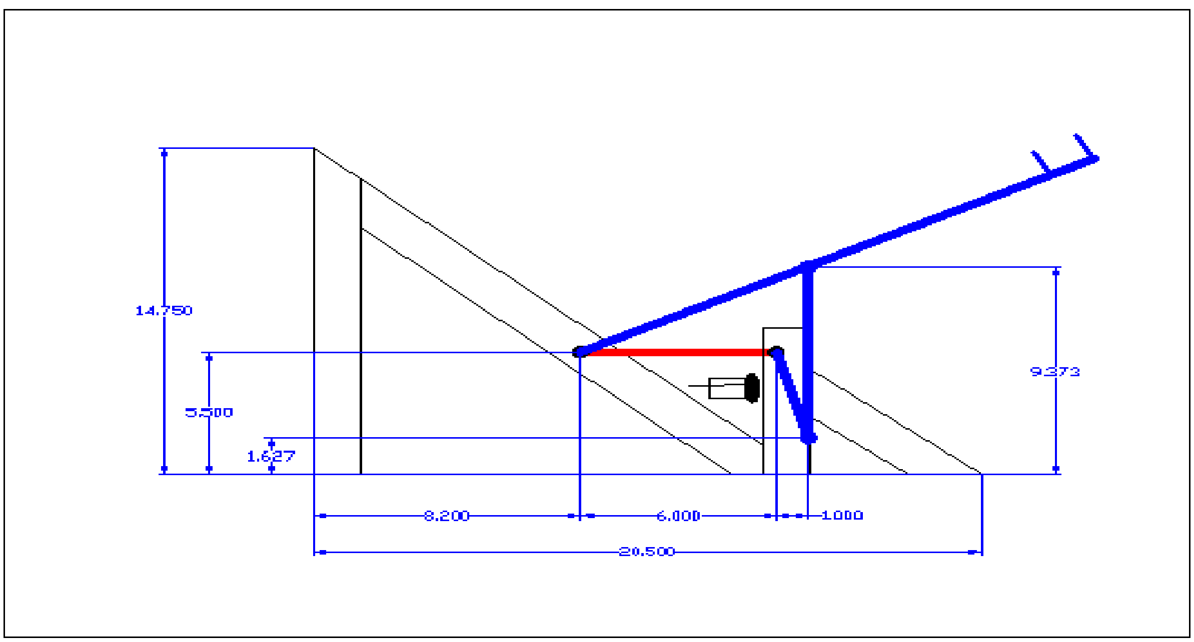


Figure 3-10. Graph showing the releasing point of the model.

Figure 3-10 show a 4 bar mechanism in releasing point. The minimum input angle is –75.522° and the minimum output angle is 28.955°. Bar 1, R1 is 6.5 in; bar 2, R2 is 4 in; bar 3 R3 is 8 inch and bar 4 R4 is 8 inch.

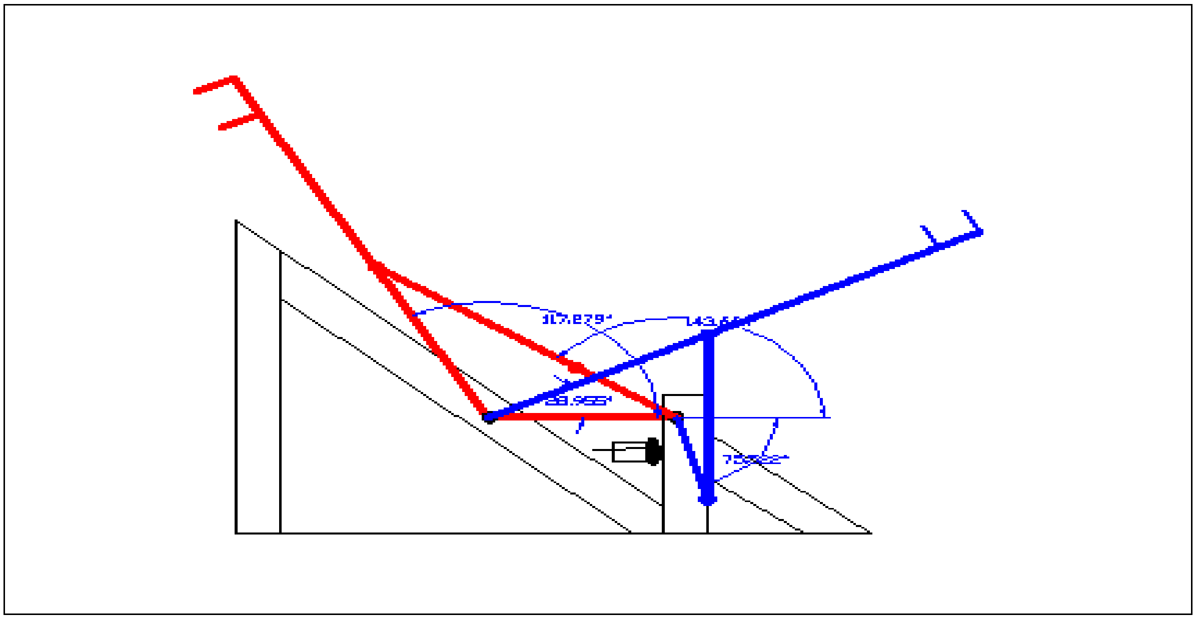


Figure 3-11. Graph showing the limiting position for our mechanism.

Figure 3-11 shows our 4 bars mechanism compared in motion limit. The maximum input angle is 143.664° and the maximum output angle is 117.279°; the minimum input angle is –75.522° and the minimum output angle is 28.955°. Bar 1, R1 is 6.5 in; bar 2, R2 is 4 in; bar 3 R3 is 8 in and bar 4 R4 is 8 in.

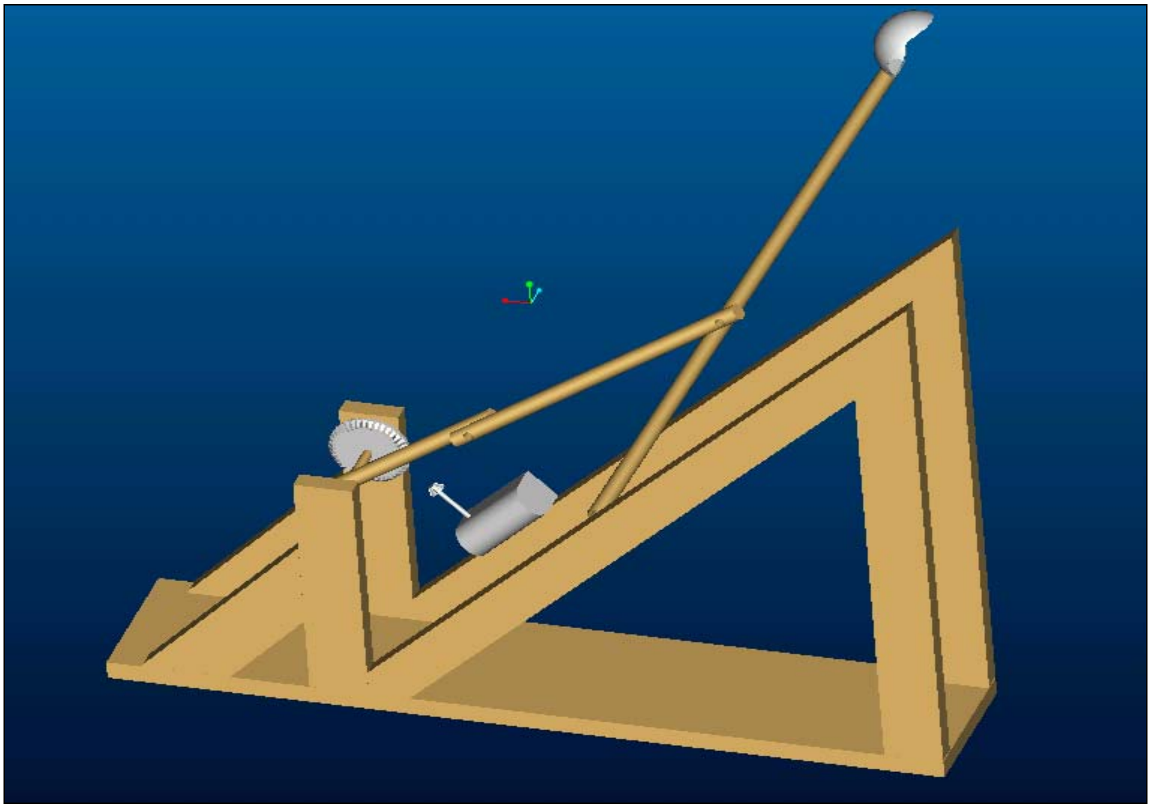


Figure 3-12. Graph showing our model in 3D. Generated using Pro-Engineering software.

The Virtual analysis group was successfully utilized the use of software especially ADAMS to assist our design of the model. We successfully simulate our model in ADAMS and see how the model works before we actually built it. We also made a modification for the model that suggested by analysis group, which is to elongate spring element instead of compress it. This is because from our ADAMS analysis, we found that a elongate spring will give us a larger angular velocity than a compression spring for a same spring stiffness. After we use ADAMS analyze our model, the model was send to the manufacture group to manufacture it. The release mechanism of this system was unsolved by the time the model was sent to manufacture group. However, the manufacture group said they would be responsible for the design of the release mechanism. Our analysis is not enough, if given more time; we could have explore more features that is available in ADAMS which we can use in our design.

Besides this, we use a lot of ideas that we ideas that we have learn in our machines and mechanism class. Among the most is the idea of limiting position for a given type of Grashofs linkage. This part of the virtual analysis was done in MATLAB. Where we can see how the angle change when we change the length of the links.

We did enjoy learning using ADAMS doing this project. The model that we have come out with in this short period of virtual prototyping may not be the best model. We should do more works to better improve our model. In the future, we should use the ADAMS to do the optimizing process for us, and more systematically record the entire model that is available for analyze. The ADAMS software is very user friendly we can learn it easily for basic analysis problem like this type. The only problem that we have been facing using ADAMS is the default unit convention that this software used.

4. Manufacture process:

The manufacturing portion of the project consisted of three sections, materials testing, mechanism construction, and testing.

Materials Testing:

During the materials testing phase of the construction, the elastic materials were tested extensively. The rubber bands were tested for unstretched length, maximum length, and spring stiffness. The result of the testing was included in the Table 6.

Table 4-1. Summary of the testing result.

No.	Type	Unstretched Length(cm)	Stretched Length(cm)	Weight (g)	k (kg/s^2)	Max Length(cm)
1	Medium Blue	5	10.5	375	0.668182	15
2	Medium Red - Thick	6	15	375	0.408333	20
3	Medium Red - Thin	6	21.5	375	0.237097	24
4	Medium Natural	6	18	375	0.30625	24
5	Medium Green	5	20	375	0.245	20
6	Medium Yellow	6	22	375	0.229688	22
7	Medium White	5	13	375	0.459375	16
8	Large White	8	40	375	0.114844	40
9	File Band	17	30	375	0.282692	72
10	Cable Wrap	10				30
11	Bungee	28	34	375	0.6125	70

Gear ratio = 336:1.

The torque that we use is 53 Nm.

Revolution per minutes = 30 rpm.

Voltage supplied = 3 V DC.

The unstretched length was simply a measurement of the non-loaded rubber bands. Stretching the rubber band to the limit of elastic deformation, and then measuring the length determined maximum length. To measure the stiffness of the rubber bands, bags of pennies were used. The exact weight of the pennies was known, the information being gathered from the US mint website. A bag of pennies was hung on the rubber band, and then the elastic deformation was measured. Using the equation F=kx, the stiffness was determined by dividing the force by the amount the rubber band stretched.

Mechanism Construction:

The construction started with data received from the analysis group, which provided a design for joint positions and link lengths. The manufacturing group had to design a mechanism around the given design that would complete the objectives of the project. A support structure and release mechanism had to be designed, as well as designing the actual joints and links.

The steps in the construction are as follows:

1. Materials:

The fist step in this process was to select materials. Since the motor was not moving the supports structure, weight issues were not a concern. 1.5” by .75” wood was chosen for this purpose. The links, however, required a strong, as well as light, material because the motor would be accelerating them. More energy used to move the links meant less that could be used to propel the ball. Three different sized dowels were chosen, because the input link had to withstand more bending stress than the follower, and the follower more than the coupler. Finishing nails were used for the joints due to the fact that they are small, smooth, and would produce little friction. A differential gear (from a hobby shop, used on radio controlled cars) with a 3 to 1 gear ratio was used. This ratio was chosen because of the original contest rules that stated that there was a two-turn limit for the motor.

2. Support structure:

The support structure was then designed. Two right triangles were chosen, because it was a simple yet sturdy design that could fit all the joints necessary. The larger triangle in the front of the mechanism contains the first ground pivot point, as well as the rubber band contact point. The second triangle contains the second ground pivot point, including the gear contact, motor mount pivot, and the release mechanism pivots.

3. Release mechanism:

The concept for the release mechanism is as follows: when the input link comes down to the point of release, it will release a rubber band that holds the motor against the differential gear. Another rubber band is pulling the motor in the opposite direction at the same time, so when the input ling triggers the mechanism and releases the first rubber band, the motor is pulled away from the differential, stopping the mechanism.

4. Ball holder:

The ball holder was made using the used toilet paper roll. This is because it was light and free. The base of the ball holder was made using a thick paper cut into round shape.

5. Switch: The switch was a 12 V switch capable of handling up to 10 A.
6. Power supply: we use two batteries of 1.5 V connected in series to produce a total voltage of 3 V.

The final model was shown in Figure 4-1 below.

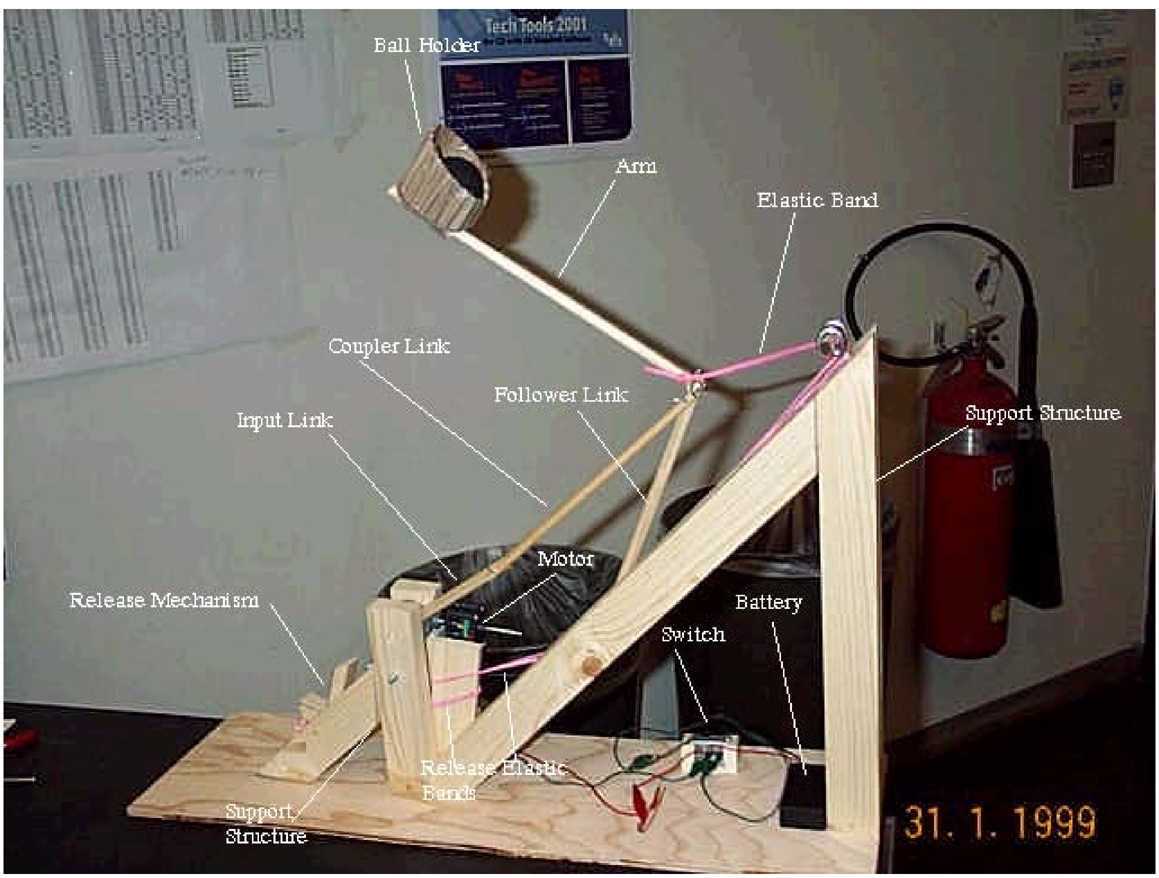


Figure 3-1. The final model of the mechanism.

Testing:

The last phase of the manufacturing section was that of testing. Different rubber band lengths, stiffness and configurations were tested to achieve maximum distance. This testing was done, while still considering the limitations of the motor.

Run time	Distance (inch)
1	108.7
2	106
3	107.5
4	106.8
5	107.8
6	107.5
7	106.8
8	107.4
9	107.6
10	107.3
11	107.8
12	107.4
13	107.5
14	106.9
15	107.7
Average:	107.38

.

Note: This testing result shows that the average range that our ball can shoot is around 107.38 inch. From this testing, we can also see that our model is behaving quite stable. (This testing was done by placing the model on the ground. In the competition, we are placing the model on the table, so the distance in the competition will be higher than this value)

COMPETITION PERFORMANCE:

After testing on our model we found that there are some problems with our design. These problems are mainly due to the construction of the mechanism. We thus prepared a checklist for the competition. We found that if we followed the checklist before we started the mechanism, the model would work with no problem.

The following are the checklist items that we have determined.

Table A .Checklist for Competition.

Steps	Item to check	Remark		
		Trial 1	Trial 2	Trial 3
1	The rubber band does not restrict the movement of the motor.	Yes	Yes	Yes
2	The rubber band is place at its maximum height.	Yes	Yes	Yes
3	The gear is tied on the motor.	Yes	Yes	Yes
4	Both gear are tied together closely.	Yes	No	Yes
5	The ball is in the ball holder.	Yes	Yes	Yes

We found that if all five items are checked, our mechanism will perform well. However, in the competition, the second attempt was unsuccessful. This was due to limited time for preparing of the mechanism. We failed to complete the entire checklist before the second attempt. We immediately found the mistake by reviewing the checklist and observing that we failed to perform step #4.

Our mechanism launched the ball a distance of 113 inches during the first attempt and 114 inches during the third attempt. We were unsuccessful during the second attempt. From the results of the two successful launches, we can say our model is very stable and consistent. The two successful attempts show that our mechanism is very predictable and reproduces the same results for every launch. This is a very important characteristic when designing a model for competition. You would want a machine that performs the same every time with no surprises so you can evaluate the mechanism and find way to improve its design.

Compared with other groups, we found that our mechanism had a shorter setup time between launches. Also, the time between turning the motor on and launching the ball was shorter for our mechanism. This is the major advantage of our mechanism. For such a simple mechanism, we were able to launch the ball the fourth farthest distance among the 14 groups. If the other groups were required to use less time between turning the motor on and launching the ball, we would have finished first in the competition.

The constructed mechanism met all of the requirements for the project:

1. It is fully made of woods (except the nails used in connecting the members).
2. The cost of construction is very low. The total cost of materials and the motor was less than $30.
3. It uses things that are easily found around the house. For example, our ball holder is made of a toilet paper roll, which has the advantages of being both very light and inexpensive.
4. We used only one motor, with a voltage supply of 3V (2 AA size batteries).
5. No preloaded energy for launching the ball.
6. The entire structure is within the 2 ft. by 2 ft. operating window.

The performance record for the whole competition was also included below for reference.

	COMPETITION PERFORMANCE				JUDGES' RANKING OF TEAMS				
Group No.	Trial 1	Trial 2	Trial 3	Comments	JUDGE 1	JUDGE 2	JUDGE 3	JUDGE 4	JUDGE 5
1	425"	450"	401"	Overtime on trial 3	2	3 (Tie)	4	3	3
2	69"	75"	71"		6	8	5	8	5
3	0	0	0		13	13	13 (Tie)	12	12
4	163"	159"	166"	Overtime	4	7	2	5	1
5	19"	18"	17"		11	14	12	13	N/A
6	241"	229"	236"		1	2	1	2	4
7	113"	114"	0"		7	3 (Tie)	10	9	N/A
8	62"	61"	0"		14	9	13 (Tie)	14	9
9	102"	102"	90"		8	5 (Tie)	7 (Tie)	4	8
10	86"	63"	77"		9	10	9	10	10
11	62"	62"	55"	Overtime on 2 runs	10	11 (Tie)	6	7	7
12	0	0	72"	Round 2	12	11 (Tie)	11	11	11
13	229"	233"	208"		3	5 (Tie)	3	1	6
14	64"	38"	67"		5	1	7 (Tie)	6	2

Table 4-1. Competition performance result adapted from MAE412 class website.

CONCLUSION:

This project was completed successful with the cooperation of each group members. The final performance of our model is what we have predicted. The weakness of our design was also examined after the competition. The weakness for our design is that we need to check all the items in our checklist each time we want to launch the ball. That is, we have some weakness on the construction of the structure. This also results in the competition performance where the two gears was not hold tied together and thus we missed the launching.

This mechanism can be improved for utilize the 20 second motor run time. In our model, we optimize our motor turning design base on the constraints of 2 revolutions before the ball launched. When this constraint is changed to 20-second motor run time, we decided not change our design when this constraint was changed. If we could have time to modify our mechanism, we will probably utilize this advantage in our design. Beside this, we found that the analysis part can be improve by more utilized the software Adams. In this project, we only use Adams in assisting our model design and we found that it is actually very powerful software. If more time was given to explore this software, we could rely our design more on this software.

In this project, we use most of the theory that we learn in this class to analyzed our model. Also, because of this, we limited our mechanism to one that can be analyzed by using the theory that we learn in this class. We found that the theory of Grashof Criteria is very useful in the beginning of design. In the model that we have generated, we decided to use a Crank-Rocker to pull our elastic band, to satisfy this, the shortest link must be place beside the ground link. From here, we can limit the possible combination of linkages to a few. This criterion also makes our optimization process greatly simplified, as shown in the Virtual Prototype section.

The theory of limiting position for different Grashof linkage was also very useful is assisting our design. Since we need a Crank-Rocker, the limiting position for this linkage will be only for the output link where the input link has no limit of motion.

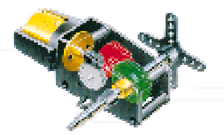
However, to utilize the 2 revolution per second, we decided to use a two gear combination, in which one the gear on the motor turn two round where the output will give a more than 180 degree turn. This is in turn used in our mechanism. By using the limiting position theory, we can determine how the output link angle changes when we change the length of the coupler link.

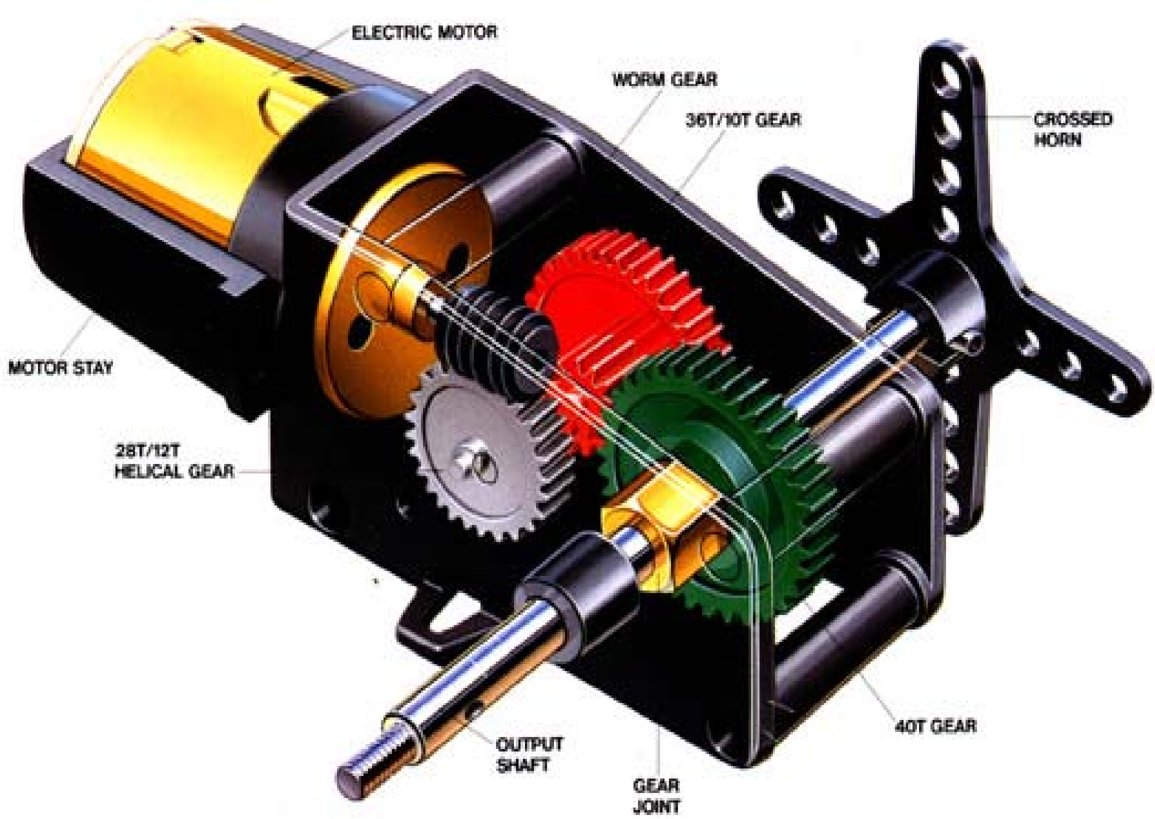
We have learned a lot by doing this project. This project not only gave us a chance to use the theory that we have learned in this course but also explore us to a very useful software, which is Adams. Beside this, we have found that the technique of loop closure equation is much more convenient to use if we want to write a program that can be use for all general case. The mathematical formulation for the four bar mechanism is also useful for us to reduce a very lengthy mathematical equation to a few constant in which error can be minimized.

We appreciate this project and we would also like to take this opportunity to thanks our professor, Dr Krovi, in helping us throughout the design of this project.

APPENDICES:

1. The motor specification used in our Project.

Ratings (@3 VDC)			 (Click for large image)
	216:1	**336:1**	
Torque N-m (oz-in)	0.33(47.22)	0.53(75.00)	
RPM	48	30	
No Load Current	220 mA		
Dimensions (mm)	Body: 31 x 76 Shaft: 80		



For further details see: http://www.hvwtech.com/gearsets.htm

2. The MATLAB command for synthesis method use in Analysis section.

```
%****************************************************
%   TO ADJUST THE COUPLER LINK LENGTH, ADJUST
%   LINK R3.  CHANGE IT BELOW TO VARY ROCKER ARM
%   MOVEMENT.  REMEMBER, TO BE A CRANK-ROCKER,
%   S+L < P+Q (GRASHOF CRITERION)
%****************************************************

a=4;  % r2 (INPUT LINK)
b=9;   % r3 (COUPLER LINK)   VARY R3 TO FIND RANGE FOR ROCKER
c=8;   %r4  (FOLLOWER/OUTPUT LINK)
d=6;    %r1  (GROUND LINK)

theta=0*pi/180;
Ax=a*cos(theta), Ay=a*sin(theta), Dx=d;Dy=0;

K1= (b^2+d^2-c^2-a^2)/(2*(d-Ax));
K2= (2*Ay)/(2*(d-Ax));
K3=K1-d;

P=K2^2+1;
Q=2*K2*K3;
R=K3^2-c^2;

By1= (-Q + sqrt(Q*Q-4*P*R))/(2*P);
By2= (-Q - sqrt(Q*Q-4*P*R))/(2*P);

Bx1= K1 + K2*By1;
Bx2= K1 + K2*By2;

th3_1= atan2((By1-Ay),(Bx1-Ax))*180/pi;
th4_1= atan2((By1),(Bx1-d))*180/pi;
th3_2= atan2((By2-Ay),(Bx2-Ax))*180/pi;
th4_2= atan2((By2),(Bx2-d))*180/pi;

X1=[0,Ax,Bx1,Dx]; Y1=[0,Ay,By1,Dy];
X2=[0,Ax,Bx2,Dx]; Y2=[0,Ay,By2,Dy];

figure(1); plot(X1,Y1,'r-',X1,Y1,'ro');axis([-12 12 -12 12]);
disp('Press any key to proceed');

pause

ind=1;

for t=180:-10:0,

theta=t*pi/180;
Ax=a*cos(theta); Ay=a*sin(theta); Dx=d;Dy=0;

K1= (b^2+d^2-c^2-a^2)/(2*(d-Ax));
```

```
K2= (2*Ay)/(2*(d-Ax));
K3=K1-d;
P=K2^2+1;
Q=2*K2*K3;
R=K3^2-c^2;
By1= (-Q + sqrt(Q*Q-4*P*R))/(2*P);
By2= (-Q - sqrt(Q*Q-4*P*R))/(2*P);

Bx1= K1 + K2*By1;
Bx2= K1 + K2*By2;

th3_1= atan2((By1-Ay),(Bx1-Ax))*180/pi;
th4_1= atan2((By1),(Bx1-d))*180/pi;
th3_2= atan2((By2-Ay),(Bx2-Ax))*180/pi;

th4_2= atan2((By2),(Bx2-d))*180/pi;
X1=[0,Ax,Bx1,Dx]; Y1=[0,Ay,By1,Dy];
X2=[0,Ax,Bx2,Dx]; Y2=[0,Ay,By2,Dy];

figure(1); plot(X1,Y1,'r-',X1,Y1,'ro');axis([-12 12 -12 12]);
%M(:,ind) = getframe;

ind=ind+1;
disp('Press any key to proceed');

pause
end

%movie(M);
```

3. *Matlab command for finding the position, velocity, and acceleration using the equation that we have derived in the Analysis section.*

```
%*****************************************************
%       LOOP CLOSURE METHOD FOR POSITION
%*****************************************************

a=4;  % r2 (INPUT LINK)
b=9;   % r3 (COUPLER LINK)   VARY R3 TO FIND RANGE FOR ROCKER
c=8;   %r4  (FOLLOWER/OUTPUT LINK)
d=6;    %r1  (GROUND LINK)

r1 = d;
r2 = a;
r3 = b;
r4 = c;
r5 = 5;

g = 32.2;
t1 = 0;
t2 = 20*pi/180;
phi = 110*pi/180;    %angle between follower link and ball holder
link
t2d = 30 *2*pi/60;
t2dd = 10;

A = (2*r1*r4*cos(t1))-(2*r2*r4*cos(t2));
B = (2*r1*r4*sin(t1))-(2*r2*r4*sin(t2));
C = (r1^2)+(r2^2)+(r4^2)-(r3^2)-
(2*r1*r2*(cos(t1)*cos(t2)+sin(t1)*sin(t2)));

T_1 = (-B+(B^2-C^2+A^2)^(0.5))/(C-A);
T_2 = (-B-(B^2-C^2+A^2)^(0.5))/(C-A);

t4_1 = 2*atan(T_1);
t4_2 = 2*atan(T_2);

num_1 = r1*sin(t1)+r4*sin(t4_1)-r2*sin(t2);
den_1 = r1*cos(t1)+r4*cos(t4_1)-r2*cos(t2);

num_2 = r1*sin(t1)+r4*sin(t4_2)-r2*sin(t2);
den_2 = r1*cos(t1)+r4*cos(t4_2)-r2*cos(t2);

t3_1 = atan2(num_1, den_1);
t3_2 = atan2(num_2, den_2);

the3 = t3_2;    %pick which theta3 to use
the4 = t4_2;    %pick which theta4 to use
```

```
%**********POINT OF INTEREST***********************
%  rcx = r1*cos(t1) + r4*cos(t4) - r5*cos(t4+phi)
%*************************************************

phi = (110*pi/180) - the4;
rcx = (r1*cos(t1))+(r4*cos(the4))-(r5*cos(phi));
rcy = (r1*sin(t1)) + (r4*sin(the4)) + (r5*sin(phi));

%*******OUTPUT TO SCREEN, POSITION OF BALL*********
rcx
rcy
%*************************************************

%*************************************************************
%       VELOCITY ANALYSIS USING LOOP CLOSURE
EQUATIONS(DIFFERENTIATING)
%*************************************************************

L = [-r3*sin(the3) r4*sin(the4); -r3*cos(the3) r4*cos(the4)];
N = [r2*sin(t2)*t2d; r2*cos(t2)*t2d];
M = (L^-1)*N;
t3d = M(1,1);
t4d = M(2,1);

vcx = (-r4*sin(the4)*t4d)-(r5*sin(phi)*t4d);
vcy = (r4*cos(the4)*t4d)-(r5*cos(phi)*t4d);

%**********OUTPUT: VELOCITY OF BALL HOLDER****************
vcx
vcy
%*********************************************************

%*************************************************************
%ACCERLERATION ANALYSIS USING LOOP CLOSURE
EQUATIONS(DIFFERENTIATING 2X)
%*************************************************************

E = [-r3*sin(the3) r4*sin(the4); -r3*cos(the3) r4*cos(the4)];
G =
[(r4*cos(the4)*t4d^2)+(r2*sin(t2)*t2dd)+(r2*cos(t2)*t2d^2)+(r3*co
s(the3)*t3d^2); (r4*sin(the4)*t4d^2)+(r2*cos(t2)*t2dd)-
(r2*sin(t2)*t2d^2)-(r3*sin(the3)*t3d^2)];

F = (E^-1)*G;

t3dd = F(1,1);
t4dd = F(2,1);

acx = (-r4*sin(the4)*t4dd)-(r4*cos(the4)*t4d^2)-
(r5*cos(phi)*t4d^2)-(r5*sin(phi)*t4dd);
acy = (r4*cos(the4)*t4dd)-(r4*sin(the4)*t4d^2)-
(r5*cos(phi)*t4dd)+(r5*sin(phi)*t4d^2);
```

```
%***********OUTPUT: ACCELERATION OF BALL HOLDER****************
acx
acy
%***********************************************************
```

4. *Matlab program for Force analysis.*

```
%*************************************************************
%               FORCE ANALYSIS USING FREE BODY DIAGRAMS
%*************************************************************
a2 = 2;
a3 = 4.5;
a4 = 4;
c2 = cos(t2);
s2 = sin(t2);
c3 = cos(the3);
s3 = sin(the3);
c4 = cos(the4);
s4 = sin(the4);

xdda = ((-t2dd/2)*sin(t2))-((t2d^2/2)*cos(t2));
ydda = ((t2dd/2)*cos(t2))-((t2d^2/2)*sin(t2));

xddb = -(t2dd*sin(t2))-(t2d^2*cos(t2))-(3/2*t3dd*sin(the3))-
(3/2*t3d^2*cos(the3));
yddb = (t2dd*cos(t2))-(t2d^2*sin(t2))+(3/2*t3dd*cos(the3))-
(3/2*t3d^2*sin(the3));

xddd = -(1.25*t4dd*sin(the4))-(1.25*t4d^2*cos(the4));
yddd = (1.25*t4dd*cos(the4))-(1.25*t4d^2*sin(the4));

H = [1 0 -1 0 0 0 0 0 0;
   0 1 0 -1 0 0 0 0 0;
   a2*s2 -a2*c2 a2*s2 -a2*c2 0 0 0 0 1;
   0 0 1 0 -1 0 0 0 0;
   0 0 0 1 0 -1 0 0 0;
   0 0 a3*s3 -a3*c3 a3*s3 -a3*c3 0 0 0;
   0 0 0 0 1 0 1 0 0;
   0 0 0 0 0 1 0 1 0;
   0 0 0 0 a4*s4 -a4*c4 -a4*s4 a4*c4 0];

I = [m2*xdda; m2*(ydda+g); I2*t2dd; m3*xddb-Fs; m3*(yddb+g);
I3*t3dd; m4*xddd-Fs; m4*(yddd+g); I4*t4dd]

J = (H^-1)*I;
```