MAE 412 – Machines and Mechanisms 2: Catapult Project
12/13/02

Michael Kurczewski
Nicholas Larratta
Jonathan Leahy
Nicholas Leone
Kuan Kiong Lim
William Louisos
Arturo Machuca
Jeremy Malik
Introduction:

The group’s task was to create a catapult system in order to propel a squash ball the furthest distance. A competition was organized in order to compare the performance of each group’s design. Each group was given a set of constraints to follow while generating their design:

- The catapult system must contain at least a 4-bar mechanism while accomplishing its task. More than four links is allowed, but the mechanism must be at least a 4-bar.
- Each group is also limited to one standardized 3-4.5 VDC electric motor with 216:1 and 336:1 gearing ratios in order to power the system.
- The entire mechanism must be made out of wood for ease of construction and to prevent an overwhelming need of assistance in the machining shop.
- The entire mechanism must operate within a 2’x2’x2’ window, including the base plate that it is mounted to. Throughout the launching process, no part of the mechanism may leave the 2’x2’x2’ window.
- The base plate of the mechanism must have substantial room available such that it can be clamped to a table with two C-clamps.
- No part of the mechanism may cross the “starting plane” from which the distance traveled by the squash ball will be measured.
- The mechanism may only be touched to turn power on to the motor and after the projectile has been thrown. Therefore, a release mechanism is needed for automatic firing.
- Purchases are to be kept to a minimum and all parts should come from “student’s houses/apartments/garages, machine shops, scrap yards, etc.”
- The projectile must be released within 30 seconds of power being turned on.
• For the “precision shooting” portion of the competition, a standardized garbage can would be placed at five-foot increments, specified prior to launch by the group, and at a minimum of ten feet.

Idea Generation:

After initially sitting down and discussing the constraints and goal of this project, we immediately discarded certain ideas: the use of the motor to directly drive a link due to its low speed, and the use of a mechanism with more than 4 bars due to the complexity of construction and analysis. Then we began to discuss our options of using a slider-crank to push the ball or using a link of a traditional 4-bar to throw the ball. Initially we ruled-out the 4-bar throwing the ball due to a slightly set back release point and the potentially inconsistent release angle and direction. A slider-crank would allow the ball to release from the mechanism at the most forward position of the operating window, potentially gaining one foot of travel distance over throwing the ball. The slider-crank would also guarantee that the ball was released at a 45-degree angle and traveling directly forward.

Building off the slider-crank idea, we drew up some sketches for potential designs. For maximum distance, the projectile would have to be released at a 45-degree angle, so we drew a ramp extending to opposite corners of the 2’x2’ operating window. Extending the ramp from corner to corner allows for the maximum travel for the projectile during release, which could potentially allow more force to be applied. This was the standard template we used to generate different designs. Variables for subsequent designs were: 4-bar placement, type of energy storage, release mechanisms, and placement of motor attachments.

Our first design included the input link to be almost the entire length of the base (2 feet) and the coupler link to be relatively short. The ramp would be constructed such that there would be an
open slot down the center for the input and coupler links to travel. A pulley system would be developed to attach the motor to the connection joint between the input and coupler link. The idea behind this design was to give the motor the largest moment-arm on the input link, making it easier to store energy. To reduce friction between the slider and the ramp, we decided to add wheels or casters to the slider.

![Figure 1: Slider-Crank with Torsional Spring](image)

As for a type of energy storage, we developed several types. Our first thought was to use a torsional spring at the ground pivot of the input link. The spring would be attached such that it was in its undeformed state when the slider was at the top of the ramp. As the motor pulled the input link back toward the base, energy would be stored in the spring. When the pulley released, the input link would receive a rotational input from its ground link.
The second idea was to use either a compression or tension spring attached between the input link and ground. The same idea would apply as it did for the torsional spring, except the linear springs would apply a linear force while the torsional spring would apply a rotational force. We decided to discard torsional springs since they are not as common and were less familiar to us than linear springs.

![Slider-Crank with Linear Springs](image)

The third idea generated for this design was to store energy in the form of a lifted weight. The potential energy of the weight would be the driving force of the slider-crank. For this configuration, the weight would be directly connected to the slider, such that two feet of travel by the weight would result in two feet of travel by the slider. The motor would pass through a pulley and also be directly connected to the weight. A release mechanism would be developed such that as the weight reached the top of the ramp, the line connecting the motor to the weight would be
released and the weight would drop and propel the slider up the ramp. The 4-bar mechanism in this configuration would mainly serve as a stabilizer, keeping the slider moving in

![Figure 3: Weight-Driven Slider-Crank](image)

a controlled direction. Of these three designs, the linear spring seemed to be the most practical, allowing for different amounts of energy storage by using different types of springs and adjusting their placement.

As the mechanism was constructed, problems arose with attaching the springs to the input link and were alleviated by attaching them to the slider and the ramp. Therefore, tension springs were used to “pull” the slider forward and propel the ball. Upon testing, we decided to try inverting our design and use the end of the input link to “throw” the ball and use the slider to move along the base for controlled movement. This alteration was considered after intuitively thinking that one can “throw” a ball further than one can “shot-put” it. The same tension springs were used to pull the slider, which in turn, caused the input link to throw the ball. This final design was chosen as it performed better than our initially constructed design.
Figure 4: Final Design of Slider-Crank Mechanism
**Construction:**

**Platform:**

As a base for the catapult ¼ inch plywood was selected because it was easy to cut and provided a solid platform for connecting the components of the slider crank. It was cut in a 24” x 24” size so it would be easy to see if the slider crank moved beyond the two-foot window.

**Link arms:**

The input crank and coupler were both constructed of ¼ inch plywood and cut to lengths of 22 inches (with an effective link length of 11.3 inches) and 8 inches respectively. The ends of the links were rounded using a jigsaw and holes were drilled 1 inch apart on the input crank to provide adjustability for the precision throwing part of the competition.

The arms were connected by steel shafts with threaded ends from which nuts and washers were attached. The input link was then connected to two wood blocks, which were attached to the plywood base.

Eyehooks were then attached to each side of the ground link and each side of the coupler link. These provided the connection points for the springs, which supplied the force for the throwing arm.

The squash ball holder was made from the cap of a spray paint can with the top half of the cap was cut off for clearance purposes. It was attached to the end of the input link by running wire through the cap and hole on the link.

**Slider:**

The slider in our design consisted of two wheels attached to the end of the coupler link by a threaded steel shaft, similar to the design used to connect the other link. Graphite was put on the shaft to reduce friction between the wheels and the coupler link. In fact, this method of lubrication
was used in all of the link connections because traditional grease does not work well with wood on metal applications.

**Release mechanism:**

The release mechanism was a relatively simple design. It consisted of a piece of music wire with a circular loop from which the string running from the motor was attached. One of the ends was bent into an L-shape, which was placed in a hole at the end of the input link. The other end, which was completely straight, was designed to hit a block placed near the motor. The force from the impact would push the L-shaped end out of the link, thereby releasing the string being pulled by the motor. The drawing below illustrates the design.

![Figure 5: Release mechanism design](image)

**Figure 5: Release mechanism design**

**Motor connections:**

The motor was connected to two sets of two D batteries in parallel configuration and then connected to a three switch, which could run the motor in forward or reverse. A shaft attached to the gearbox acted as the pulley for our Kevlar string, which pulled the input crank down, thereby tensioning the springs.
Figure 6: Final Design After Construction – Please refer to CD for additional pictures and movies of our Initial Design and Final Design
Analysis equations:

Velocity Equation

\[
\begin{aligned}
[ -r_3 \sin \theta_3 & \quad r_4 \sin \theta_4 ] \begin{bmatrix} \ddot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} = \\
[ -r_3 \cos \theta_3 & \quad r_4 \cos \theta_4 ] \begin{bmatrix} \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} &= \\
\begin{bmatrix} r_2 \dot{\theta}_2 \sin \theta_2 \\ r_2 \dot{\theta}_2 \cos \theta_2 \end{bmatrix}
\end{aligned}
\]

Acceleration Equation

\[
\begin{aligned}
[ -r_3 \sin \theta_3 & \quad r_4 \sin \theta_4 ] \begin{bmatrix} \dddot{\theta}_3 \\ \ddot{\theta}_4 \end{bmatrix} = \\
[ -r_3 \cos \theta_3 & \quad r_4 \cos \theta_4 ] \begin{bmatrix} \ddot{\theta}_3 \\ \ddot{\theta}_4 \end{bmatrix} &= \\
\begin{bmatrix} r_2 \ddot{\theta}_2 \sin \theta_2 + r_2 \dot{\theta}_2^2 \cos \theta_3 & r_3 \dot{\theta}_3^2 \cos \theta_4 - r_4 \dot{\theta}_4 \cos \theta_4 \\
2 \quad & 2
\end{bmatrix}
\end{aligned}
\]

Position

\[
\begin{aligned}
A &= 2r_1 r_2 \cos \theta_1 - 2r_m r_4 \cos \theta_m \\
B &= 2r_1 r_3 \sin \theta_1 - 2r_m r_4 \sin \theta_m \\
C &= r_1^2 + r_4^2 - r_r^2 - 2r_1 r_m (\cos \theta_1 \cos \theta_m + \sin \theta_1 \sin \theta_m)
\end{aligned}
\]

The hand analysis equations are derived in Appendix B. More sophisticated testing than would be required to determine the exact value of the velocity and acceleration of the slider. Once these values were estimated, they can be inserted into the derived equations for a complete position, velocity, acceleration, and force analysis.
Performance/Conclusions:

With a maximum throw of twenty feet in the distance throwing competition and no targets hit, our device was not as successful as we had hoped. There were a few design flaws that became evident as the competition progressed that could be easily fixed if we had the opportunity to redesign our catapult. Our slider consisted of two wheels attached to one of our links. Two springs were connected to the same link as the slider, and the motor was attached to the other link. We made the mistake of offsetting the force of the springs and the force of the motor, causing the slider to veer off to one side if not set up properly. Initially, this problem was not evident, but with continued testing, fatigue began to take its toll and warped our link as well as the axle used for our wheels. When the slider did not move in a straight line, the catapult had a tendency to not throw as far as it did in our initial testing. Our catapult could be redesigned to have both the spring force and the motor force on the same link, and a track could be constructed for the wheels to travel on. This would ensure that the slider moved in a straight line every time.

The cup we used to throw the ball was also a serious design flaw that unfortunately came as a result of redesigning our device after discovering our initial slider-crank was unsuccessful. We initially had created a cupped area in the slider of our initial device for the ball to be launched from. In testing, this consistently threw the ball at a 45-degree angle, but our slider-crank was inconsistent and had a tendency to bind, resulting in throws under ten feet on a regular basis. After our redesign, we had a problem devising a cupping device that would consistently throw at a 45-degree angle after the motor was attached. We eventually had to settle for a modified cap from a spray paint can, but this design idea was unsuccessful in competition. Our low trajectory throws resulted in three missed targets in the accuracy competition, and a decreased throwing distance in the maximum throw competition. In hindsight, we should have constructed a customized cupping device that could have been fastened to the input link to increase stability and result in more consistent releases.
Our release mechanism could be improved as well. We used a piece of bent welding rod connected to the motor to pull down our four bar mechanism. As the release hit a piece of wood, it was forced off our launching arm, and the catapult would throw the squash ball. This at times resulted in inconsistent throws because the release had a tendency to not let go of the link smoothly. A more sophisticated triggering mechanism would have resulted in more consistency for both the distance and accuracy competition.

During the competition, we were probably too conservative with our choice of springs to use for the catapult. We were concerned with how much of a load the motor would be able to pull in the 30-second time limit, and we elected to stay away from stiffer springs. Since we had a third motor that we had not used, we probably should have taken a chance and put our set of stiffer springs on the device. If the motor was able to pull back the stiffer springs in close to (but over) the 30-second time limit, we could have always modified our release mechanism so that the catapult would release earlier. The stiffer springs would allow more energy to be stored, and a much greater force would have been exerted on our four-bar, resulting in longer throws.

We feel that our device was successful in satisfying some of the constraints given at the beginning of the competition (time to shoot, size, utilizing the motor, etc.). However, we could have optimized our design to get better results in competition. Had we made most of the changes discussed, our catapult would have been much more successful than it was. If we were presented with an opportunity to redesign our device, all of the above changes would be made and tested to ensure their success.
Appendix A – Design Simulations  
(please refer to disk for AVI files of each simulation)

Design Consideration 1

Figure A-1 - Slider Crank Catapult
Slider crank catapult system using a linear spring and torque engine to impact squash ball.
AVI file illustrating the dynamic simulation of initial design AVI movie #1.

Specifications / Components

1  Input Link Arm – 12 x 1 x ½ inches
2  Coupler Arm – 8 x 1 x ½ inches
3  Slider – 2 x 2 x 2 inches
4  Linear Spring k – 38 lbf / inch
5  Torque motor - .4N m
6  Gear to Gear ratio 1 to 5 (1 inch to 5 inch)
7  Release angle at 45 degrees

Maximum Throwing Range
1  Maximum Range using Dynamic Simulation – 22 feet
Design Consideration 2

Figure A-2 - Slider crank using a weight system

Slider crank using a weight and pulley to impact the squash ball.
AVI file illustrating the dynamic simulation of our second design AVI movie #2.

Specifications / Components

1. Input Link Arm – 15 x 1 x ½ inches
2. Coupler Arm – 6 x 1 x ½ inches
3. Slider – 2 x 2 x 2 inches
4. Hanging Mass – 20 lbs
5. Torque motor - .4N m
6. Pulley - 5 inch diameter
7. Release angle at 45 degrees

Maximum Throwing Range

1. Maximum Range using Dynamic Simulation – 19 feet
Design Consideration 3

Figure A-3 - Slider crank on track

Slider crank mechanism using a track and slider cup to throw a squash ball. AVI file illustrating the dynamic simulation of our third design AVI movie #3.

Specifications / Components

1. Input Link Arm – 18 x 1 x ½ inches
2. Coupler Arm – 4 x 1 x ½ inches
3. Slider – 2 x 2 x 2 inches with cup for squash ball placement
4. Linear Spring (2) k – 20 lbf / inch
5. Torque motor – constant angular velocity of 4 degrees / sec. Equivalent to 15 second wind up time
6. Released at 45 degrees

Maximum Throwing Range

1. Maximum Range using Dynamic Simulation – 21 feet
Design Consideration 4

Figure A-4 - Final Design Choice

Slider crank utilizing simple spring and torque motor system.
AVI file illustrating the dynamic simulation of our final design AVI movie #4.

Specifications / Components

1. Input Link Arm – 20 x 1 x ½ inches
2. Coupler Arm – 7 x 1 x ½ inches
3. Two Wheels – 2 inch radius
4. Linear Spring k – 20lbf / inch
5. Torque motor – constant angular velocity of 4 degrees / sec. Equivalent to wind up time of 15 seconds
6. Release angle at 75 degrees

Maximum Throwing Range

1. Maximum Range using Dynamic Simulation – 26 feet