# A PROJECT REPORT
# ON
# Dynamic System

## MSE 222 - Kinematics and Dynamics of Rigid Bodies and Mechanisms

| Group 22 | Student ID |
|---|---|
| Haowen Li | 301316951 |
| Junaid Khan | 301308300 |
| Martin Kuppers | 301301213 |
| Danny Qiu | 301282388 |

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# 1.0 Introduction

The intent of this project was to design, analyze, simulate, and test a dynamic system that transports a ball from one corner of a given vertical slab to the other. The main objective of this project was to ensure that the ball took an average of 3-5 seconds to complete its total displacement, while passing through several required course components. The dynamic system had to include at least one of each of the following: a rotating element, a spring, a curved path, two changes in direction, and an impact. Moreover, the dynamic system should be passive, and the ball's motion should be initiated without any user contact – i.e. using only the spring. After satisfying the design requirements and objective of this project, the dynamic system was to be simulated using MATLAB to ensure that the real and simulated time of the dynamic system were to within a reasonable degree of error. The purpose of this report is to provide details about our design, fabrication and simulation processes.

# 2.0 Design

This section of the report provides detailed information on how the dynamic system was assembled with all the required components to achieve the main objective of this project - an average time of 3-5 seconds for transporting the ball from one end of the slab to the other.

## 2.1 Preliminary design

Figure 1 shows the preliminary design that was submitted as part of project submission on March 8th.
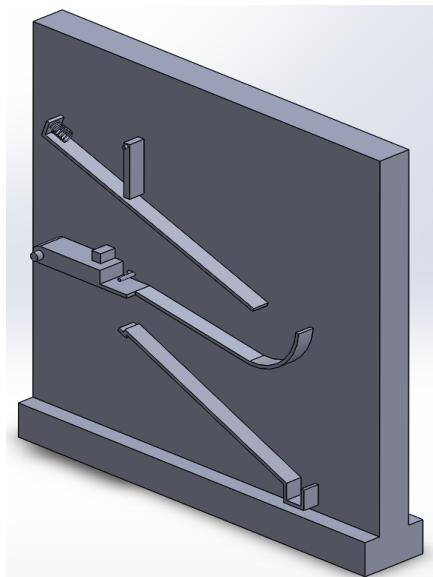
*Figure 1. Submitted preliminary design*

The design shown in figure 1 was accepted by all team members as an initial submission. However, after submission, the group came to realize that the design would not be accepted at the demo because the ball would not start at rest - due to the slope, the ball will accelerate due to gravity. The project required that the ball's motion was not to be interrupted by any human intervention and the ball's motion was to be initiated by a compressed spring. Due to the described reasons, we consider our next figure as our original preliminary design. This design went through several implemented solutions to achieve the project objective.

With the help of solidworks motion analysis, ensuring that the design was able to give us the optimum time, we came up with a preliminary design. The motion analysis showed that the design can give us an approximate time of 2.75 seconds. Therefore, taking into consideration that the material to be used in fabricating the design and the ball to be used can add extra time, we accepted our preliminary design and moved forward with the fabrication process. Figure 2 shows an updated version of the submitted preliminary design.



*Figure 2. Corrected preliminary design*

Our initial concept, as can be seen in the above figure, contained only the simplest components required. Our thought process in designing this was to ensure the project requirements were fulfilled while mitigating the necessary calculations. Therefore, using a solidworks model, we finalized this design - as it met the time requirements and included all the necessary components.

However, upon completing the fabrication process, as shown in figure 2, our design encountered several problems. Namely,

- Over-rotation of the lever arm
- Much faster than anticipated
- Bouncing on the curved path after impact
- Not enough kinetic energy at the last horizontal path to make it up the slope.

## 2.2 Design Update - I

All in all, the initial design wasn't as optimum as we expected it to be - as the time requirements were not fulfilled. Following are the initial solutions that we devised to increase the time taken by our dynamic system to transport the ball from top left corner to the bottom left corner.

- Removed initial impact - there are several other locations of impact along the path.
- Reduced slope height for final horizontal path - so ball has enough energy to make it over.
- Added stops for the rotating part.

Figure 3 bellow shows the implementation of these initial suggested solution.
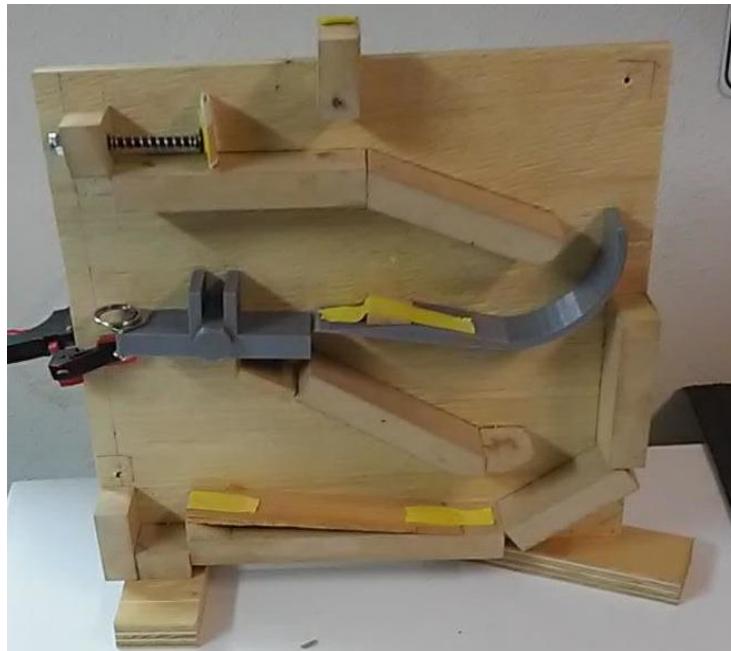


*Figure3. Implementation of initial suggested solutions to our preliminary design*

Our initial suggested solution as shown in figure 3 consisted of removing the initial impact as it required too much force for the ball to go past it and hence it was hard to get an optimal initial speed for the ball, ultimately affecting the total time. We also sanded the end slope's top - to help the ball make it over into the stop ditch. The result of this stage was that it was easier to control the initial speed of the ball. Unfortunately, controlling the initial speed wasn't enough to reach the time requirements of the project as the ball was still covering the distance in a very short period. Moreover, upon implementation of this suggested solution, we realized that we cannot ignore the rotating rod impact at the start as it is a crucial component for illustrating the use of an important equation in kinematics - coefficient of restitution.

## 2.3 Design Update - II

Taking into consideration all the results that were obtained in the previous stage, our group devised a second solution to tackle the problems - achieving optimum time with the rotating impact at the start. Following, is the second stage of suggested solutions to our preliminary design.

- Add two extra paths - increasing the time for transporting the ball.
- Add a more gradual slope at the end path - for a constant deceleration at the end.
- Put the rotating rod at its original position - required for coefficient of restitution application.

Figure 4 bellow shows the implementation of these second stage of suggested of solutions to our preliminary design.



*Figure 3. Implemented second stage of solutions to the preliminary design*

The second stage of revision to the preliminary design is shown in figure 4. The revision consisted of including the initial impact as it was part of the project requirement. The two extra paths were not added until after the first test carried out with the initial impact - without the two extra paths, the ball was being transported to the end zone swiftly. Addition of the two extra paths and the gradual slope for constant deceleration of the ball, resulted in optimum time of about 3 seconds - which is the main objective of this project. Therefore, upon achieving this objective, we accepted the second stage of revision to our preliminary design as our final design for this project.

## 2.4 Final Design

Figure 5 shows the final product that was assembled and used for the project demo and the MATLAB simulation. The dimensions of the final design is attached in Appendix 1.



*Figure 4. Final design for the dynamic system*

# 3.0 Calculations

One of the objectives of this project was to simulate the motion of the ball in our dynamic system using MATLAB. MATLAB can approximate the analysis of the motion of the ball to a certain degree of accuracy – dependent on the variables taken into consideration that affect the motion of the ball. This section of the report is dedicated to putting forth all the assumptions and the equations that were used in MATLAB to simulate the motion of the ball for each respective element of the dynamic system. Figure 6 is used as a reference for this section of the report.
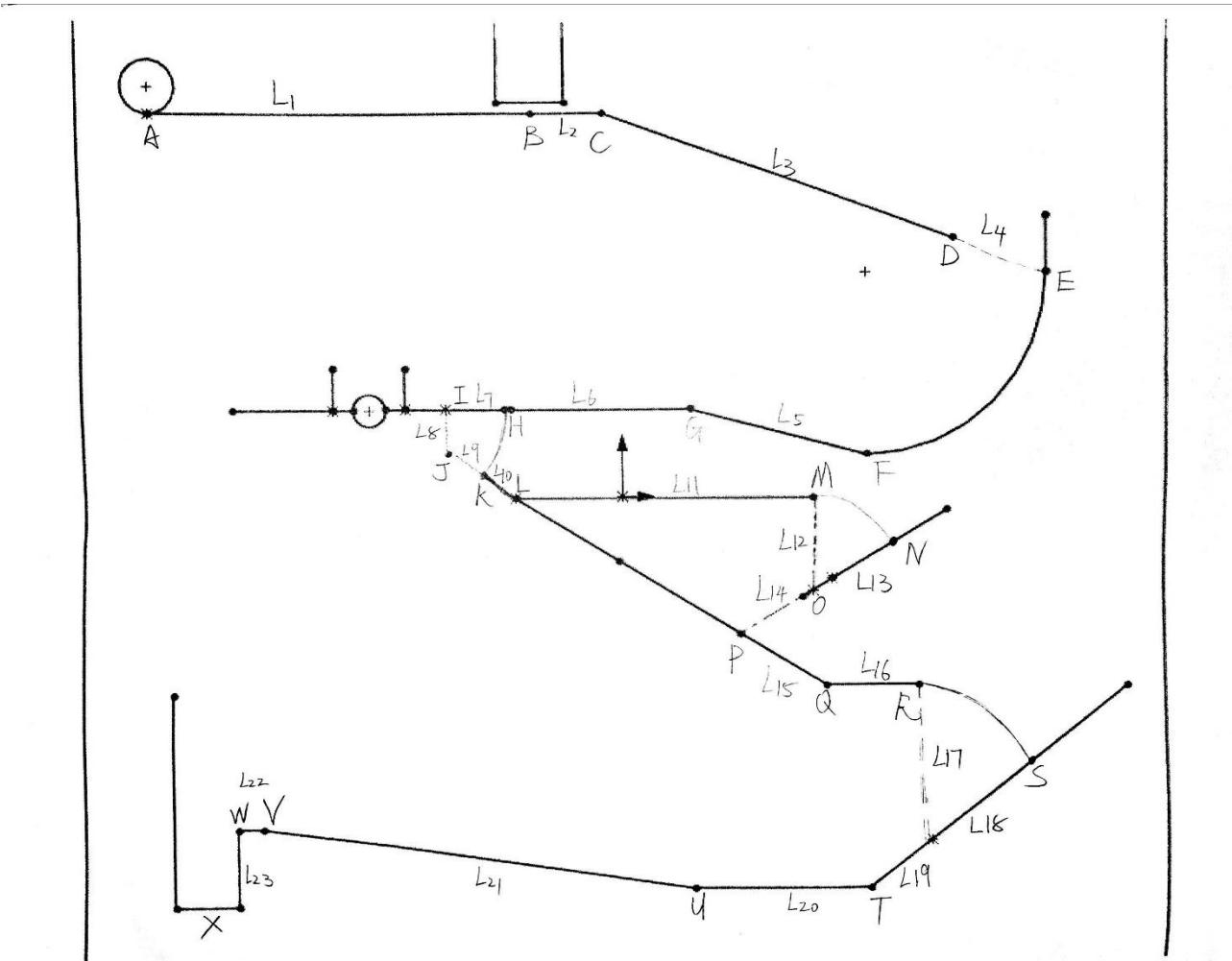


*Figure 6. Components and Equations for each element*

## Spring

The motion of the ball in our system is initiated by the collision between a compressed spring and the stationary ball. We consider the ball and the spring as a single system and apply the conservation of energy equation, since the only forces acting on this system are conservative forces. The following equations provide the initial velocity of the ball at the point A given by the compressed spring, where $k$ is the spring constant, $\Delta d$ is the deformation of the spring, $m$ is the mass of the ball and $v$ is the velocity of the ball.

- $Elastic\ potential\ energy = \Delta E = \frac{1}{2}k\Delta d^2$
- $Kinetic\ Energy = \frac{1}{2}mv^2$
- $Final\ Energy = Initial\ Energy$
- $\frac{1}{2}m_{ball}V_{ball}{}^2 = \frac{1}{2}k\Delta d^2$
- $V_{ball} = \sqrt{\dfrac{k}{m_{ball}}} * \Delta d$

## Horizontal Path

In our dynamic system, it was assumed that the ball was rolling without slipping. With this assumption, we were able to ignore the effect of friction on the motion. Moreover, eliminating the work done by air resistance, we were able to make the conclusion that the velocity of the ball remains constant when it rolls on horizontal paths. The following equations govern the behaviour of the ball along paths AC, GH, LM, QR, TU and VW. In the following equations $t$ is the time variable, and $(t)$ stands for a function with respect to time.

- $Acceleration\ (t) = 0$
- $V\ (t) = V_{initial}$
- $S(t) = v_{initial} * t$

## Impact

As the ball moves along AB, it encounters a stationary rod at point B, as shown in figure 6. The collision between the rod and the ball is more like an elastic collision, so that the coefficient of restitution was assumed to be some number less than but close to 1. To analyze the motion of the ball before and after the impact with the stationary rod, we assumed that the angular momentum

of the system about the fixed point of rotation of the rod, is conserved. By solving the following equations, the velocity of the ball after impact and the tangential velocity of the rod after impact can be yielded. In the equations, $H_p$ is the angular momentum about the pivot of the rotating rod, $I_{rod}$ is the mass moment of inertia of the rod about its pivot, $e$ is the coefficient of restitution, $\omega$ stands for angular velocity, $m$ stands for mass, and L is the length of the rod (L is also the radius of rotation of the rod, since the pivot is fixed at the top end of the rod).

$$Conservation\ of\ Angular\ Momentum: \left(H_p\right)_{Before\ Impact} = \left(H_p\right)_{After\ Impact}$$

$$m_{ball} \cdot V_{ball,\ before\ impact} \cdot L = I_{rod} \cdot \omega_{Rod,\ after\ impact} + m_{ball} \cdot V_{ball,\ after\ impact} \cdot L \ \text{①}$$

$$I_{rod} = \frac{1}{12} m_{rod} L \ \text{②}$$

$$\omega_{Rod,\ after\ impact} = \frac{V_{ball,\ after\ impact}}{L} \ \text{③}$$

Substituting equation ② and ③ into ① yields:

$$m_{ball} \cdot V_{ball,\ before\ impact} \cdot L$$

$$= \frac{1}{12} m_{rod} L \cdot \frac{V_{ball,\ after\ impact}}{L} + m_{ball} \cdot V_{ball,\ after\ impact} \cdot L \ \text{④}$$

$$Coefficient\ of\ Restitution: e = \frac{V_{Rod,\ after\ impact} - V_{ball,\ after\ impact}}{V_{ball,\ before\ impact} - V_{Rod,\ before\ impact}} \ \text{⑤}$$

Solving ④ and ⑤ yields the values of $V_{Rod,\ after\ impact}$ and $V_{ball,\ after\ impact}$.

Moreover, to simplify the calculations, we assumed that the ball experiences inelastic collisions at point E, I, K, N, P, S, and X. In this case the ball does not bounce back at those positions, and we also assumed that the velocity of the ball becomes zero after the collisions at E, I, N, P, S, and X.

## Inclined Path

Again, in our dynamic system, it was assumed that the ball was rolling without slipping on an inclined path. The following equations govern the behaviour of the ball along paths CD, GF, KL, NO, PQ, ST and UV. In the following equations $t$ is the time variable, and ($t$) stands for a function with respect to time.

From Newton's second law the following equations are governed, where $m$ is the mass of the ball, $a$ is the linear acceleration of the ball, $\alpha$ is the angular acceleration of the ball, $r$ is the radius of the ball, $\tau$ is the torque exerted by the static friction at the point of contact of the ball with respect to the center of mass of the ball, and $I$ is the mass moment of inertia of the ball at the center of mass of the ball:

$$a = \frac{Fnet}{m} = r\alpha = \frac{r\tau}{I} \; ①$$

The torque at the center of mass of the ball can be expressed in friction ($F_f$) and the ball-radius:

$$\tau = r * F_f \; ②$$

Substituting ② into ① gives:

$$F_f = \frac{I * Fnet}{m * r^2} \; ③$$

Using the sign convention by which this force is positive, the net force in the direction of the ball's velocity is:

$$Fnet = Fgravity - F_f \; ④$$

Expanding ③ in ④ yields:

$$Fnet = \frac{Fgravity}{1 + \dfrac{I}{m * r^2}} \; ⑤$$

The $F_{gravity}$ is a force component due to gravity in the same direction as the inclined path:

$$Fgravity = m * g * sin(\theta) \; ⑥$$

Where $g$ is gravity, and $\theta$ is the angle of the inclined path with respect to a virtual horizontal line. The mass moment of inertia of a solid ball is:

$$I = \frac{2}{5}mr^2 \; ⑦$$

Substituting ⑤, ⑥ and ⑦ into ① yields the expression for the linear acceleration of the ball:

$$a = \frac{m * g * sin(\theta)}{m * \left(1 + \dfrac{\dfrac{2}{5}mr^2}{mr^2}\right)} = \frac{5}{7} * g * sin(\theta)$$

Thus, for each inclined path, we have the following equations with respect to time when the ball rolls down on an inclined path:

- $a(t) = \frac{5}{7} * g * sin(\theta)$

$$V(t) = V_{initial} + \frac{5}{7} * g * sin(\theta) * t$$

$$S(t) = V_{initial} * t + \frac{1}{2} * \frac{5}{7} * g * sin(\theta) * t^2$$

When the ball rolls up on an inclined path, all the previous expressions hold except the sign of the acceleration is negative.

$$a(t) = -\frac{5}{7} * g * sin(\theta)$$

$$V(t) = V_{initial} - \frac{5}{7} * g * sin(\theta) * t$$

$$S(t) = V_{initial} * t - \frac{1}{2} * \frac{5}{7} * g * sin(\theta) * t^2$$

Moreover, since the ball rolls relatively fast, we assumed that the ball hits the curved path at E which is on the extension-line of slope CD. Likewise, the ball was assumed to hit the slope KQ at point P which is on the extension-line of slope NO. In this case, we considered the path CE and NP as two straight inclined paths so that we can apply the previous equations to make the analysis easier.

## Curved Path

The curved path (from E to F) is a quadrant of a circular arc. To estimate the motion of the ball on this path, we differentiate the central angle into a lot of tiny angles which have a same angle, and therefore they have a same corresponding chord length. Then, the curve can be replaced by those tiny chords, and the equations used for rolling down an inclined path in the previous section can now be utilized for analyzing the curved motion. Note that the velocity loss due to the uneven connections between every two nearby chords were assumed to be zero, since the slope-changes between every two nearby chords are negligible.

## Free Fall

The ball was assumed to experience two free fall motions when it falls from I to J, and from W to X. We have the following equations with respect to time when the ball experiences free fall:

$$a(t) = g$$

$$V(t) = V_{initial} + gt$$

$$S(t) = V_{initial} * t + \frac{1}{2} * g * t^2$$

## Parabolic Fall

The ball experiences two parabolic fall motions at point M and R during the whole process.
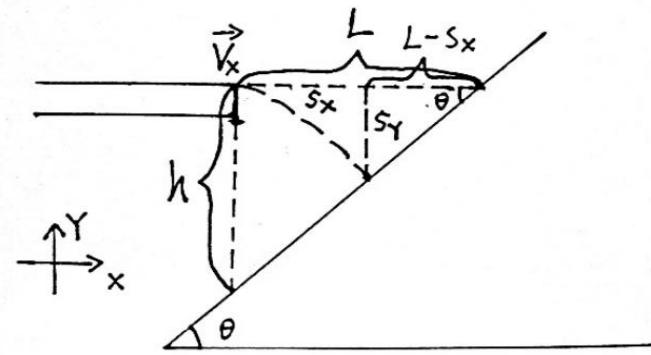


*Figure 7. Parabolic Fall*

The ball has an initial velocity $V_x$ right before it falls from the horizontal, as shown in Figure 7. The ball will have an acceleration due to gravity after it leaves the horizontal path so that it will also have a horizontal velocity component $V_y$. The equations for the horizontal displacement $S_x$ are same as the equations for horizontal paths, and the equations for the vertical displacement $S_y$ are same as the equations for free fall. The following equations express $a$, $V$, $S_x$ and $S_y$ with respect to time:

- $a(t) = g$
- $Vx(t) = V_x$
- $Vy(t) = V_{initial} + gt$
- $Sx(t) = V_{initial} * t$
- $Sy(t) = V_{initial} * t + \frac{1}{2} * g * t^2$
- $V(t) = \sqrt{Vx(t)^2 + Vy(t)^2}$

The total time for the ball to fall onto the inclined path is calculated from the following equations:

$$\frac{S_y}{L - S_x} = \tan(\theta) \ \text{①}$$

Substituting the expressions for *Sx* and *Sy* into ① yields, where $V_{initial}$ is zero:

$$\frac{\frac{1}{2} * g * t^2}{L - V_x * t} = \tan(\theta) \quad ②$$

By utilizing the quadratic function yields the expression for $T_{total}$:

$$Ttotal = \frac{-v_x * tan(\theta) + \sqrt{(v_x * tan(\theta))^2 + 2 * g * L * tan(\theta)}}{g} \quad ③$$

## Velocity Loss

The velocity losses during the motion of the ball are concerned at point C, G, J, L, Q, T, U, and V. At those point the directions of velocity of the ball change, which also causes the magnitude of the velocity to change. In other words, the ball undergoes a velocity loss when it passes by those points. We assumed that only the projection of its original velocity on its new direction will be the initial velocity in that new direction:

$$Vnew = Vold * \cos(\theta)$$

## Rotating Element

Figure below illustrates the initial setup of the rotating element.
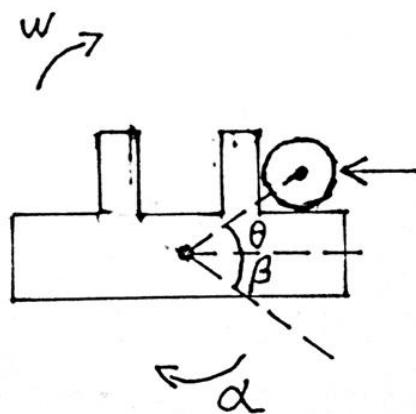


*Figure 8. Rotating Element*

For this element of the design, our assumption is that the collision between the ball and the element is elastic. Therefore, after the collision, the ball and the rotating element are assumed to be a single rigid body. Hence, the center of the rotating element is our axis of rotation. Therefore, the motion of the ball in this section of our dynamic system is purely rotational. The following equations formalize the behaviour of the ball. As mentioned above, we assume the motion of this rotating element is purely rotational and is caused by the moment produced by the weight of the respective ball. Equation 1 formalizes this behaviour.

$$\Sigma M_o = I_o \alpha \; \text{①}$$

$$\alpha = -\frac{R_{CG,ball} \cdot cos(\theta) \cdot mg}{I_{total,o}} \; \text{②}$$

The ball starts rotation at an angle of $21°$ and rotates clockwise till $-31°$. To be able to simulate the behaviour of the ball in MATLAB, the path taken by the ball about the fixed axis of this element was broken down to small segments. In doing so, the angular acceleration of the ball in each small segment can be assumed to remain constant. Breaking the path of the ball into small segments with constant increment in angle, allows the use of kinematic equations for rotational motion with constant angular acceleration.

Assuming we're currently working on a small segment of the path that is to be taken by the ball in this element, integrating equation 1 with respect to time, provides an equation for the angular velocity of the ball in this small segment. Moreover, integrating equation 1 twice with respect to time, provides an equation for the displacement of the ball. Equation 2 and 3 formulize this result.

$$\omega_f = \omega_i + \alpha * t \; \text{③}$$
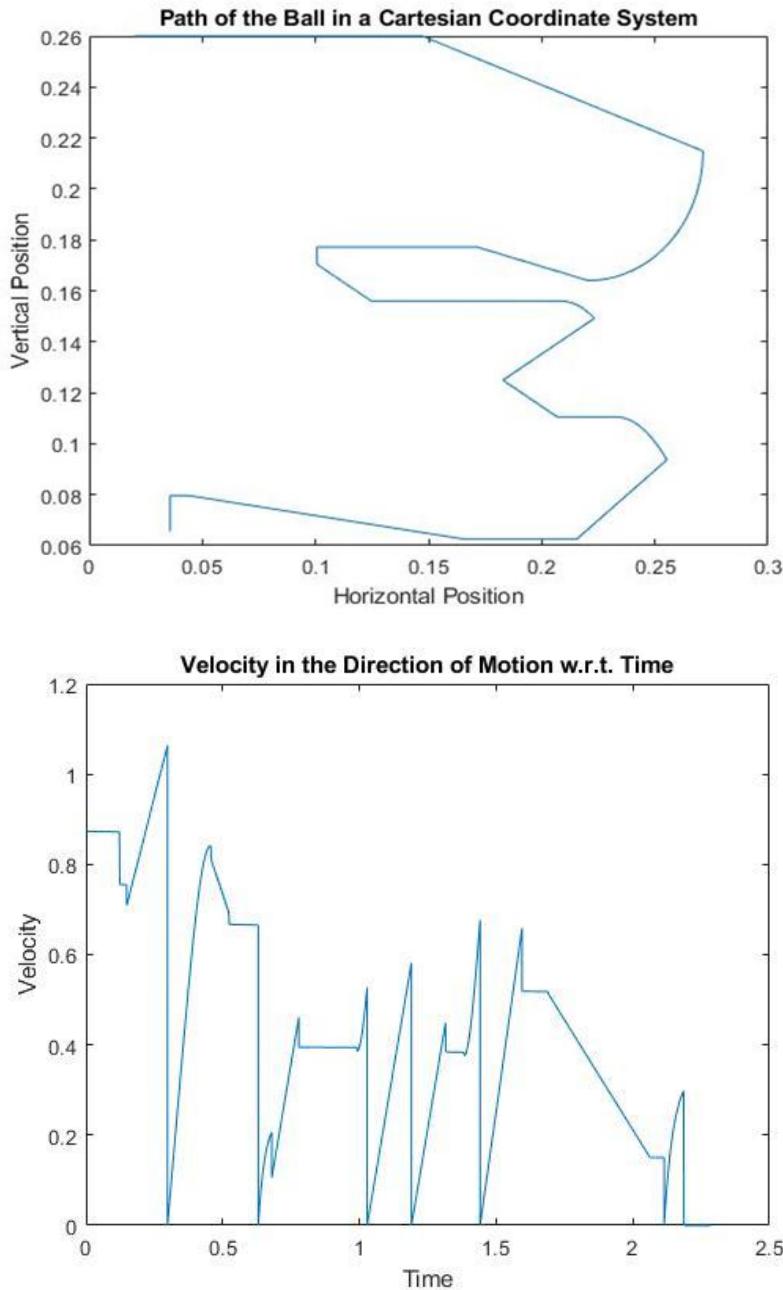
$$\theta_f = \theta_i + \omega_i * t + \frac{1}{2} \alpha * t^2 \; \text{④}$$

The angular acceleration of the ball about the fixed point of the rotating element is dependent on the position of the ball's center of gravity – it remains constant in a small segment. Equations 2,3 and 4 govern the behaviour of the ball in a small segment of the circular path taken by the ball. However, these equations can also be used for simulating the behaviour of the ball for the entire rotation by ensuring that the ball's final velocity and angular velocity for a small segment are taken as the initial velocity and angular velocity of the ball in the following segment. The

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following steps illustrate how equations 2-4 were used in MATLAB for simulating the ball's motion.

## 4.0 Results

The following graphs are the results obtained from our MATLAB simulation of our final dynamic system as shown in figure 8 under design section of this report. The behavior of each plot will be explained in detail in the section of this report.



Path of the Ball in a Cartesian Coordinate System



Velocity in the Direction of Motion w.r.t. Time
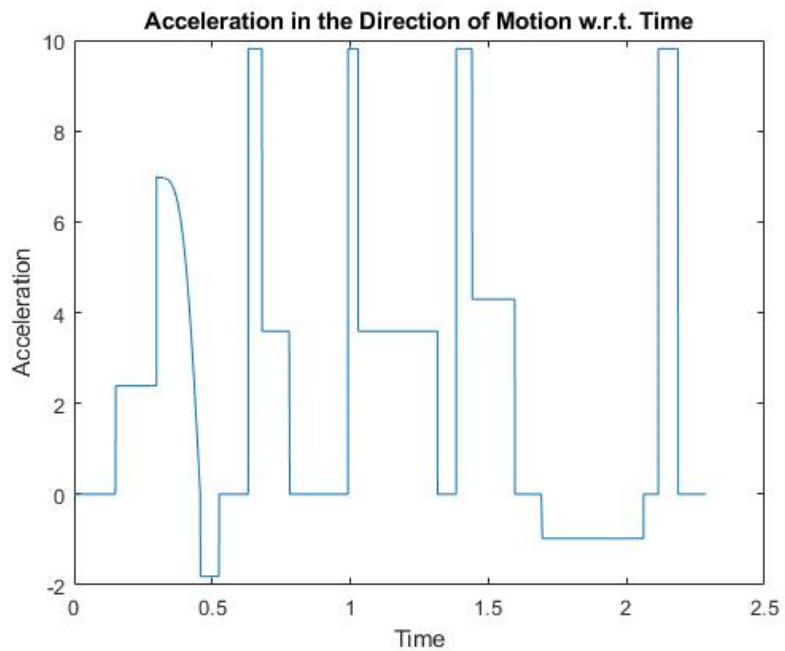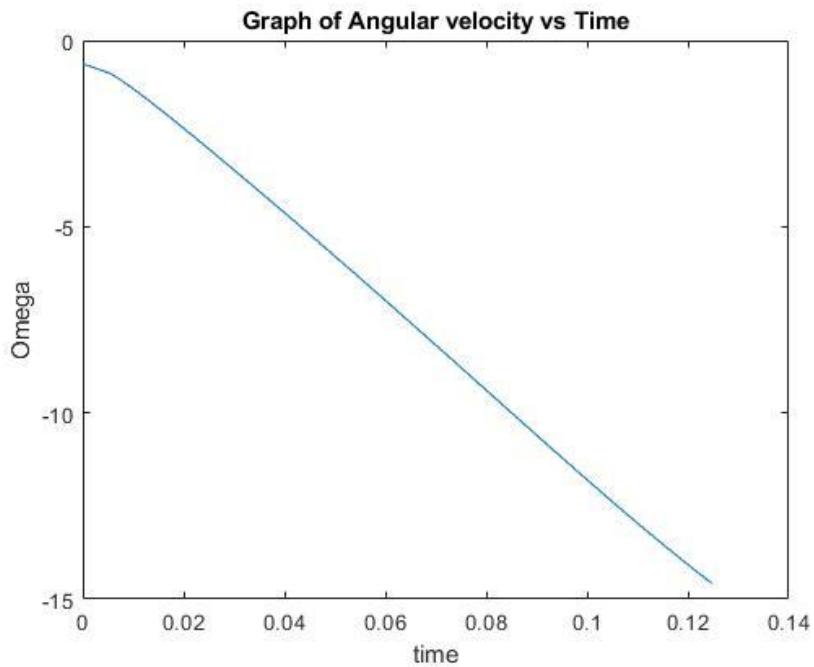
*Figure 8. Displacement, Velocity, and Acceleration of the CG of the ball w.r.t. Time*

The following results are the angular velocity and angular acceleration of the rotating element in our dynamic system. The behavior of each graph will be explained in detail in the next section of this report.
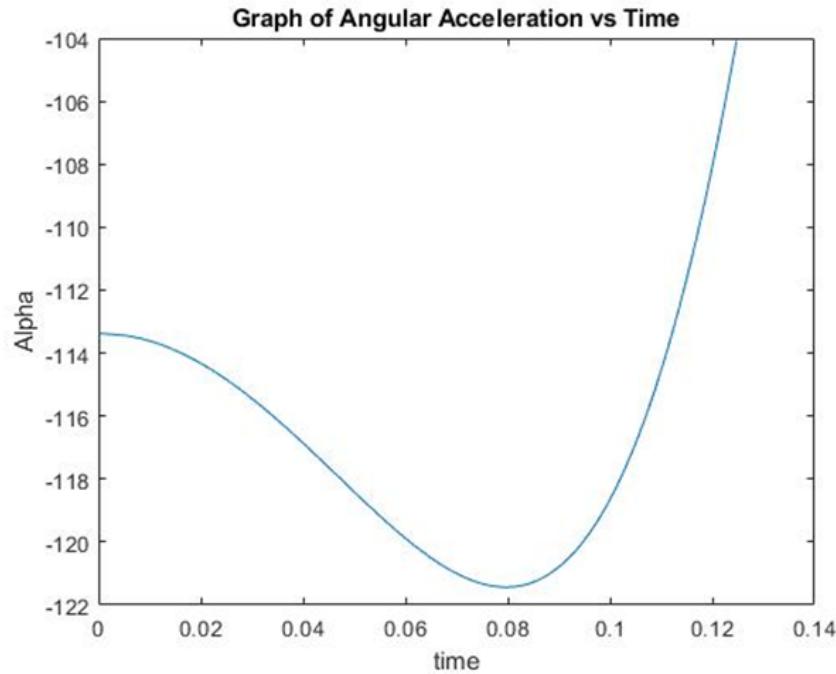
*Figure 9. Angular velocity and angular acceleration of the rotating element*

## 5.0 Discussions

### 5.1 MATLAB simulated Results

As can be seen on the graphs, the time in our MATLAB code is less than 3.0 seconds. This is due to several facts. The ball in our actual design is not perfectly constrained in the z-direction and because of this there are several tenths of a second added on to the real time. Also, the surface roughness, friction and air resistance add time. The MATLAB code is made to model a perfect situation without taking into account any of these points and hence the time in the code is several tenths of a second faster. Therefore, our MATLAB simulation is very accurate based on our assumption of ignoring some of the external interferences.

### 5.2 Component Sourcing and Characterization

This section of the report is dedicated to putting forth vital information regarding the sources of our dynamic system components. As engineers we must take into consideration the sources of each of our components and the impact these materials have or will potentially have on the

environment. Therefore, to ensure minimal effect of our materials on the environment, we used materials that had the potential to be recycled and cause little to no harm to the environment.

Recall that our dynamic system was to include at least one of each of the following elements:

- A spring - to initiate ball's motion.
- A rotating element.
- A curved path.
- Two changes in direction - left to right & down to up.
- An impact.

In the following text, we will discuss the sources of each component, their approximated duration of prior usage and how we plan on disposing the components after they achieve their purpose in our product.

## 5.2.1 Spring

The spring is a crucial part of our dynamic system as the project description clearly states that the ball must be transported from one end of the slab to the other without any user intervention. Velocity of the ball provided by the spring plays a significant role in determining the time taken for the ball to complete the track. To ensure that the ball has velocity to make it pass the rotating rod - after impact, we were looking for a strong spring - capable of giving enough kinetic energy to the ball, such that it was able to make it down the path.

Keeping in mind that our objective was to use recyclable or reusable materials, we were able to find a perfect source for our spring - a hand clipper which was previously used for pruning trees. We decided to use the spring from the hand clipper because it was readily available at our homes and after it has served its purpose in our dynamic system, it can easily be clipped back on to the same tool. The hand clipper spring was used in pruning trees for approximately a year before we planned to dismantle the clippers - to obtain the spring for our dynamic system. We plan to reassemble the hand clipper tool after the project demo so that the spring can continue to fulfill its true purpose - as a source of energy for helping the user trim their gardens.

Moreover, for our MATLAB simulation, we need to find the stiffness of our spring - the spring constant. We carried a couple of experiments with different weights attached to one end of the spring and measured the extension of the spring. Result of each experiment is tabulated in table 1.

| Experiment | Mass [g] | Compression [cm] | K [N/m] |
|---|---|---|---|
| 1 | 160 | 0.1 | 1509.9 |
| 2 | 205 | 0.2 | 1005.5 |
| 3 | 300 | 0.3 | 981.0 |
| 4 | 635 | 0.7 | 890.0 |

*Table 1. Experimental data for calculating spring constant, K*

Based on the results tabulated in table 1, the average value for our spring's stiffness was calculated to be:

$$K = 1068.28 \, [N/m]$$

## 5.2.2 Rotating Element and Curved Path

Our preliminary design - which was later modified due to the inconsistency of the results obtained, relied heavily on these two elements to provide the objective time of 3-5 seconds. Due to its major role in our dynamic system, we could not afford to have any kind of human error that was potentially available when fabricating these parts. Therefore, to get optimum precision in fabricating these components we decided to 3D print them using SFU Capstone lab services. The 3D printed components are made from Acrylonitrile butadiene styrene (ABS). ABS is a tough and extremely easy to shape material - after heating it up. It's a thermoplastic that once heated up can be easily manipulated to any desired shape. Moreover, if there is any kind of fault in the final design, ABS can be reheated and remolded into the desired shape.

SFU capstone lab has their own 3D printing services. The ABS plastic used for our component fabrication can be reheated and molded into another shape hence it is reusable. Prior to its use in

our dynamic system, ABS was used for other project components ranging from personal student projects to Engineering Capstone projects. Moreover, 3D printing a certain part has less impact on the environment compared to other machines that could have been used for the construction of our two main components in this dynamic system. Figure 10 shows the graphical representation of the environmental impact of different machines under constant use (24/7) producing the same part. [1]
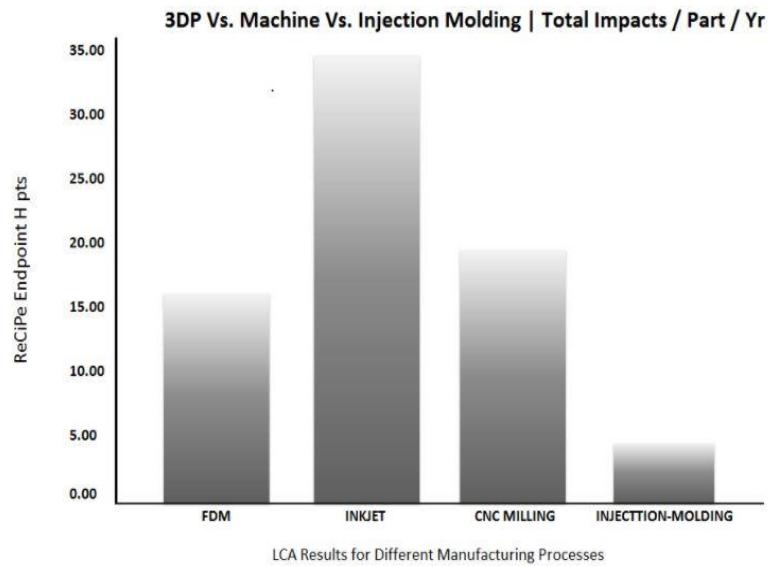


*Figure 10. Environmental Impact of different machines used for production of same component.*

Based on figure 10, injection molding has a low impact on the environment, second to injection molding. Unfortunately, 3D printing was more accessible for us - capstone lab services are free of charge.

## 5.2.3 Horizontal Paths, Ramps and Slopes

Looking back at figure 2, our preliminary design, most of our components were made up of Medium-density fiberboard (MDF) - apart from the rotating and the curve element. MDF was readily available for use in our project - group member's garage. MDF is relatively cheaper compared to solid wood and is already made from recycled wood scraps - hence an economically better source for our components. Moreover, MDF is easier to shape, has a higher density and does not have the tendency to splinter in comparison with other types of wood. Due to the characteristics of MDF, it was a perfect source for our components as they make it easy to

fabricate and sand down our components shapes with tools to be sturdy enough for our ball to be transported down the slab with the desired time of 3-5 seconds.

Although MDF was the best economically available choice, it is certainly not the most environment friendly choice. The binders and resins that are used for the production of MDF are a known carcinogen called Formaldehyde. Products containing this carcinogen are harmful to the environment as they're a gas which damages plants and crops. One of the major problems with formaldehyde are that it continues to release this gas for several years. [2] Prior to its use in our project, the MDF were used for home repair in a group member's home for approximately 5 months. The MDF used in our project will be recycled by our group member as he plans on using the material for further renovations. MDF recycling process is relatively new and currently there last resting place is landfills - where the chemicals leach out over time. [2]

### 5.2.4 Additional Horizontal Paths and Ramps

These horizontal paths and ramps were added to our preliminary design to achieve the objective time of 3-5 seconds, after the preliminary design was already fabricated. Figure 5 in Design section shows our final dynamic system. The source of these additional pieces is cedar wood. Cedar wood is relatively lightweight, cheap, and durable - all the characteristics that make it the best choice of source for our component. They were also an excellent choice of source for our components due to cedar wood's tendency to retain its stability through time - typically because of heat or dampness. Moreover, cedar wood is also environment friendly as it can be easily recycled without the production of harmful gases that could potentially harm the environment, plants and crops. [3]

Prior to its use in our dynamic system, the cedar wood, was used as roofing shingles for approximately 1 year. Cedar wood can easily be recycled by being dropped in your nearest compostable bins.

## 6.0 Conclusion

The aim of this project was to design, analyze, simulate and fabricate a dynamic system that transports a ball from one corner of the slab to the other with an average time of 3-5 seconds. Our group's prototype was able to achieve a time of 3.05 seconds during in-class demo. We were also able to simulate the motion of the ball to a certain degree of accuracy, as our simulated time
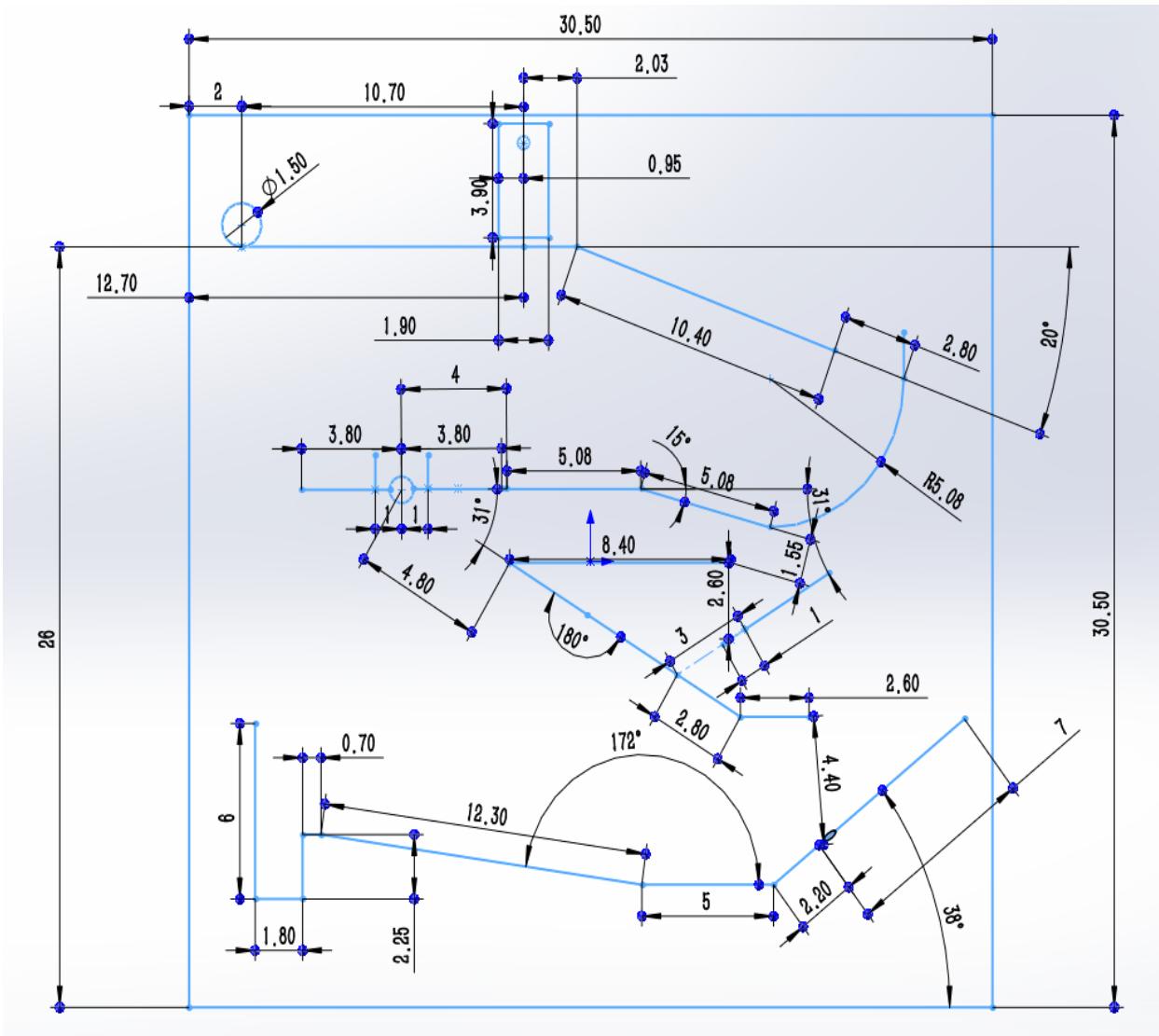
was about 2.83 seconds. The simulation of our dynamic system is reliable to a certain degree of accuracy as the percentage error between the simulated and the actual time is less than 10%. Overall, working on this project has been highly beneficial as we were able to apply in class knowledge of kinematics of a rigid body to a dynamic system.

## References

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# Appendix 1



*Dimensions for Final Design*