Module 4: Robot Wheel-Legs

Engineering Disciplines: Mechanical & Aerospace Engineering

For the Module 4 Part 1 Lab Report, each team will submit:

- Module 4 Design Worksheet completed through part H, and your Project Planning and Management Task List

For the Module 4 Part 2 Lab Report, each team will submit:

- 1 .m file containing all code for Lab 1
- 1 PDF file containing the algorithm and typed answers to Lab 1's discussion questions

For the Module 4 Part 3 Lab Report, each team will submit:

- 1 PDF file containing final wheg and adventurer image(s), the fully completed Module 4 Design Worksheet, and the final Project Planning and Management Task List

Prepare and submit these files in accordance with the ENGR 130 Style Guide and Assignment Submission Guide.

Project Planning and Management

This module is spread out over most of the rest of the term and has a great variety of tasks in it. There are many possible ways in which your team may decide to divide the work. Before you start work, read through the whole module, and plan who will take primary responsibility for the various tasks that comprise this unit.

Create your own Module 4 Project Planning Task List. Carefully read and follow all instructions in the Module 4 Project Planning and Management document. You will continue to update your task list this week and submit your task list, current as of the submission date, as part of your Module 4 Part 1 Lab Report.

In particular, if you have not already done so, make sure that two of your team members are signed up to attend a 3D printing training session at Think[Box]. This attendance is part of your team's grade for this module.

Lab 1: Simulations in MATLAB

Introduction

In designing wheel-legs (whegs), an important decision is how thick to make them. To answer that question, scientists and engineers make mathematical models of the forces that act upon the whegs when they hit the ground. A detailed analysis of those forces is too complicated for this course, but to illustrate how the process works, we will simulate a simpler system: a spherical ball bouncing on the ground. Even a ball is too complicated to analyze analytically, so we will make some further simplifications and use a numerical method to integrate the acceleration of the ball to determine the velocity and again to integrate the velocity to determine the position.

Numerical Methods

Differential equations are mathematical relationships that contain both the value of a quantity and its derivative. Some differential equations can be solved analytically, meaning a direct mathematical solution can be calculated by hand. However, most differential equations are too complex to be solved analytically. In these cases, **numerical methods** are used to approximate the solution. This may be done by a variety of numerical method techniques.

Since numerical methods often involve repetitive calculations, they are usually done via computers. In this lab you will use a common numerical method known as the explicit Euler's Method to simulate the relationship between velocity and a point's position in space. You will write MATLAB code using the explicit Euler's Method to simulate a bouncing ball.

Physical system

The following notation is used to simplify equations:

$$y' \equiv \frac{dy}{dt} = \text{velocity in the y-direction}$$

$$y'' \equiv \frac{d^2y}{dt^2} = \text{acceleration in the y-direction}$$

Suppose we want to predict the position of the ball in the vertical direction (height). When the ball is not in contact with the ground, the only force acting on the ball is gravity. When the ball hits the ground, we need to account for the force of the ground acting up on the ball, in addition to gravity. We will make some simplifications and model the ball as a discrete point of negligible radius.

We have just described the two situations we need to simulate:

a. In freefall, the downward force on the ball is $F = m\mathrm{g} = ma$. Therefore, in the freefall situation, $a = y'' = \mathrm{g}$.

b. When the ball is in contact with the ground, there will be an upward force of the ground on the ball, in addition to the downward gravitational force. The upward force can be modeled as a damper and spring system (Fig. 1). During impact with the ground the ball undergoes deformation & restitution, and the ball's velocity transitions from the downward direction to the upward direction.

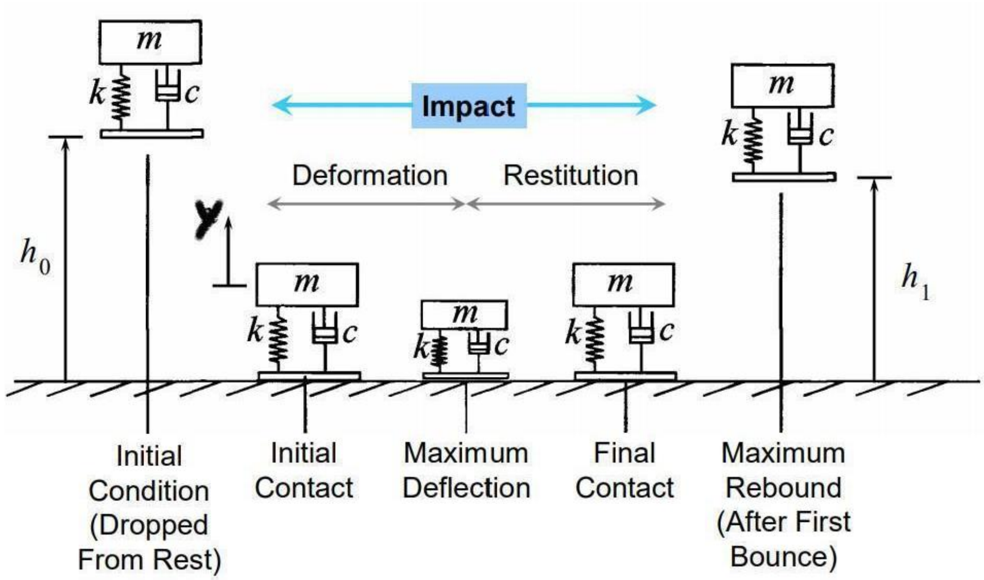

Figure 1: A mass-spring-damper model of a ball showing phases of impact at first bounce; Source

In the analysis that follows, we will define up to be the positive direction. Note that $y = 0$ corresponds to the position of the ball's center of mass at the moment of initial contact, when the ball has just touched the ground, but no deformation has yet occurred. During impact, the damping force is proportional to the ball's velocity, $F_{damp} = -cy'$. The force of the spring is proportional to the distance the ball is compressed, $F_{spring} = -ky$. (The negative signs on both forces indicate that they are in the opposite direction of the ball's velocity and position, respectively.) Both c and k are constants (Fig. 2).

By summing the forces and using Newton's Second Law:

$$ma = \sum F = F_{damp} + F_{spring} - mg$$

$$my'' = -mg - ky - cy'$$

$$y'' = \frac{-mg - ky - cy'}{m}$$

(The gravitational constant g is 9.81 m/s^2)

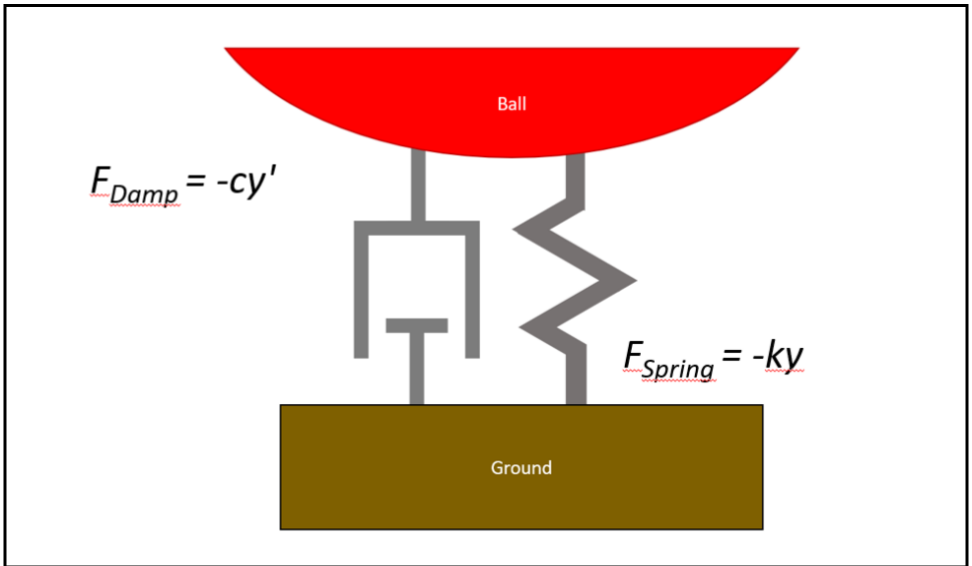

Figure 2: Damping and spring forces acting on ball during impact

We now have the accelerations of the ball during the two conditions (freefall and contact with the ground).

Euler's Method

The goal of our simulation is to predict the height throughout the ball's motion, but so far, we only have the accelerations $y'' \equiv \frac{d^2y}{dt^2}$ during each condition. To find the height, we will invoke Euler's method, which calculates the height function by stepping through time in discrete steps and calculating each point using the derivative of height, which is velocity. To find the velocity, we must also use Euler's method to calculate the velocity function using the derivative of acceleration.

$$y_{n+1} = y_n + y'_n \Delta t$$
$$y'_{n+1} = y'_n + y''_n \Delta t$$

In these equations, y_n is the current position. The subscripts *n+1*, *n-1*, etc. are all in reference to the current position.

Procedures

1. Simulate the ball dropping

a. Create an algorithm to estimate the height of the ball, *y*, for a duration of 10 seconds. Your program will produce a vector of the height of the ball, *y,* at each time step. Within the code, put in values for the following quantities: initial height (y_0), initial velocity (y'_0), time step (Δt), damping constant (*c*), spring constant (*k*), gravitational acceleration (*g*), and mass (*m*).
   i. It may help to manually write a table of y, y', and y'' vs *t* to think about how to implement your simulation in MATLAB ($y_1 = y_0 + y'_0 \Delta t$; $y'_1 = y'_0 + y''_0 \Delta t$, etc.)

ii. Ask yourself: what is y''? Does it ever change during the simulation? If so, why, and when?
iii. You will turn in your algorithm PDF as part of this lab report.

b. Now write your code. Using $m = 1$ kg, $y_0 = 1$ m, $y'_0 = 0$ m/s, $\Delta t = 0.0001$ s, $c = 2$ N·s/m, $k = 5000$ N/m, and $g = 9.81$ m/s^2, simulate the ball dropping.

c. Plot *y* vs. *t*. Make sure the plot is titled and labeled.

d. Find the minimum height of the ball during the simulation. Store this value in `min_height`.

e. To visualize the motion of the ball without damping, set $c = 0$, keep all the other arguments the same, and rerun the simulation.

f. Plot *y* vs. *t* again using the undamped *y*. Again, make sure the plot is titled and labeled.

g. Use the function `comet(x, y, p)` in MATLAB to animate the figure. The x, y inputs are the same as the `plot(x, y)` function, where the vectors are the variables we want to plot. The variable `p` dictates the animation speed between 0 and 1. For a smooth animation, use `p` = 0.01.

2. Try Different c and k Values

a. Copy your code from Part 1 above into three new sections to produce three new plots, using each of the combinations of k and c values in Table 1. Keep all the other arguments the same as in Part 1b.

Table 1: Damping and spring constants

k (N/m)	c (N·s/m)
8000	2
5000	4
5000	10

Questions

1. What is `min_height` in Part 1? Does it match what you expect to see? What physical meaning does this minimum value represent? Note: Since the ball is assumed to be a point object, deformation is negligible.

2. How long will the ball keep bouncing in Part 1e when there is no time constraint?

3. Without re-running the simulation, what will happen if you set g = 98.1 m/s^2? Will the ball bounce at all? Why or why not?

4. What about your plot changed when you changed the values of c and k? What do your results tell you about the significance of c and k?

END OF LAB 1

Labs 2 – 3: Wheel-Leg Design

Introduction

In these labs you will design a set of whegs to be 3D printed and attached to a remote-controlled car. The goal of the whegs is to help your car traverse obstacles. You will also design and fabricate another device (an “adventurer”) that will attach to the car to collect rings. During the final lab of this module, you will drive the car over an obstacle course and attempt to collect as many rings as possible. Your designs will also be judged on creativity and aesthetics.

Materials

- Calipers
- Ruler
- Computer running SolidWorks (or that is connected virtually to a computer with SolidWorks)
- Computer mouse (A mouse is needed to work effectively in SolidWorks.)

Objective

Your design challenge is to navigate a remote-controlled car through an obstacle course and collect rings. Specifically, you will design and fabricate two objects that will be attached to the remote-controlled car: a set of four whegs that will attach to the car’s axles and an “adventurer” that will grab the rings. The whegs should be designed to climb over a variety of obstacles, including tall blocks, rough terrain, and stairs. The obstacles will be made of a variety of materials. You will have an opportunity to inspect the cars, example obstacles, and rings.

Procedures

1. *Design Process Worksheet*

By filling out the Design Process Worksheet, you will complete the steps for creating your designs. You must complete Sections A through H for the Module 4 Part 1 Lab Report. You will turn in the fully completed Design Process Worksheet with your Module 4 Part 3 Lab Report.

2. *Understand the specifications for your whegs*

Your team will create four whegs according to the following specifications:

a. The whegs must be biologically inspired.
b. The whegs must be 3D printed.
c. The maximum permitted radius of a wheg is 1.75 inches.
d. The maximum volume per wheg is 1 in^3.
e. All your whegs must print simultaneously on one plate.
f. Because this design project has a competitive element, to keep everything fair, the whegs must be printed at Think[Box], using the filament provided by ENGR 130 and using the printer settings specified below.

g. You may only print your whegs once, unless the Think[Box] staff determines the printer malfunctioned during your print.
h. Once the whegs are printed, they may be modified using hand or power tools and/or the following materials: rubber bands, hot glue, paint, and tape.
i. In no case may anything be done that makes any surface of your whegs sticky or that will damage the obstacle course. ("Grippy" is OK, but sticky is not.)
j. You may use different designs for the front and rear wheels if you wish.

3. *Understand the specifications for your ring-grabbing adventurer*

a. The adventurer must mount to one of two mounting locations on your remote-controlled car.
b. The mass of the adventurer cannot exceed 45 g.
c. Your adventurer can be manufactured from any combination of the following materials: ¼" plywood, ¼" acrylic, cardboard. All materials will be provided by the Susi Lab (no outside materials are allowed).
d. You may manufacture your adventurer by laser cutting, cutting using hand tools, drilling, or any other manufacturing process available at think[box] or the Susi Lab.
e. You may add rubber bands, wood glue, hot glue, paint, or tape, provided by the Susi Lab, to your adventurer.

4. *Competition judging*

Your overall design (whegs + adventurer) will be evaluated according to the following criteria:

a. Functionality (50% of final score) as determined by the number of obstacles traversed and the number of rings that your car collects.
b. Creativity (25%) as determined by a panel of guest judges.
c. Aesthetics (25%) as determined by a panel of guest judges.

Note that your grade does not depend on your competition score.

5. *Whegs 3D printing instructions*

a. Save each unique wheg as an STL file and a PDF file.

b. Think[Box] Printing Procedures
    i. To assist the Think[Box] staff with their planning, you may only start your print during the time slot your team selected on the sign up sheet. Think[Box] open hours are here.
    ii. When you get to Think[Box] during your assigned time, you will find a 3D printer reserved for you. Make sure it has the 0.8 mm nozzle installed. Ask a 3rd-floor Think[Box] employee (wearing a green apron) for help if needed.
    iii. Follow the directions from the 3D printing training to process your STL file and print your part. You can consult the Ultimaker 2+ instruction manual if some of the details are fuzzy.

1. Set the layer height to 0.2 mm and the infill to 50%.
2. Use the ENGR 130 filament, which is stored on Floor 3 in two lockers near the laser cutters. To find the lockers, enter Floor 3 and immediately turn left. The ENGR 130 lockers are circled in the photo below. You do not need a key or code to access the filament. Again, you must use this filament.

Location of ENGR 130 filament

iv. Watch your print for at least the first layer since this is when most failures occur. If you have questions/concerns about your print, ask a student technician on Floor 3.

v. If you are there when your print is complete, unload the filament and return it to the locker.

vi. Once the whegs are printed, visit the Susi Lab during open hours and/or Think[Box] to make any modifications to the wheels that are needed. Think[Box] has a well-equipped machine shop on the 4th floor. If you are interested in getting trained on any of the shop machine tools, the schedule is linked here: https://case.edu/thinkbox/equipment/training.

Additional SolidWorks Resources

You may find the following resource helpful as you learn SolidWorks. Case students have access to the LinkedIn Learning website, which is full of instructional videos on a variety of topics.

1. Click here for information on logging into the LinkedIn Learning portal.

2. After you are logged in, search for "SolidWorks Essential Training". You will see a course for the current version of SolidWorks. Search the sections of this course to find the specific information that you are interested in studying.

END OF LABS 2 – 3

Lab 4: Test and Modify Your Designs

In today's class, you will be able to test and modify your components. You should bring your printed whegs and fabricated adventurer to class. Attach your whegs and adventurer to a remote-controlled car and practice driving on the example obstacles. Use tools and the allowable supplies to modify your design. These tools and supplies will also be available during open lab.

END OF LAB 4

Lab 5: Wheg Adventurer Competition

Today we meet on the 2nd floor of Think[Box] to test the whegs on the obstacle course and to tell the guest judges about your designs.

Materials

- Remote controlled car
- Front and back wheel hubs
- Obstacle course
- Screwdriver/drill

Procedures

1. *Prior to competition day*
   Your whegs and adventurer should be completely ready to go when you arrive for class. There will be no time to make additional modifications to them. Make sure you bring your whegs and adventurer to class!

2. *Judging for aesthetics and creativity; attaching parts to cars*
   After some short introductory comments, you will get to work! Each team will have a designated work area and will begin attaching the whegs and adventurer to the cars, following the procedure explained by your instructor. The judges for creativity and aesthetics will circulate through the work area to inspect your designs and to ask you questions.

3. *Demonstrating functionality*
   Once you attach your whegs and adventurer, you will report to the obstacle course to demonstrate the functionality of your design.

4. *Cleaning up*
   Once a team's run is complete, they are to remove their whegs and adventurer as soon as practically possible, as there will likely be other teams waiting to use the car. They are also to clean up their work area, returning all tools and equipment to their proper locations.

5. *Project planning and management task list*
   Complete and submit your final Project Planning and Management Task List with your final lab report.

END OF LAB 5