Integrated use of Programming in Machine Design Course

Dr. Michelle M. Blum, Syracuse University

Dr. Blum is interested in research in improving undergraduate engineering education; including development of student design projects, professional skills development and inclusion and outreach activities. Dr. Blum is also involved with advising and outreach. She was a founding member of the Advisory Committee for the WiSE Women of Color in STEM Program and has developed and participated in many college level outreach programs; specifically developing a hands-on activity to introduce students to the fundamental material science, mechanics and biomedical engineering through the concept of biomimicry. Her other research specializes in high performance materials development and characterization for tribological (friction and wear), structural, and biomedical applications. Her primary research interests are in the development of orthopedic biomaterials, and biomaterial characterization utilizing a combination of experimental techniques, nanoindentation, and soft material contact mechanics simulations. Understanding the structure-property relationships of biological tissues during contacting motion aids her lab in the development of synthetic biomimetic materials.

Dr. John F. Dannenhoffer III, Syracuse University

John Dannenhoffer is an Associate Professor of Mechanical & Aerospace Engineering and the Program Director of the Aerospace Engineering Program at Syracuse University. Before joining Syracuse in 2002, he worked for the United Technologies Corp for nearly 25 years.

Integrated use of programing in Machine Design Course

Abstract

This paper presents enhancements to an undergraduate mechanical engineering machine design course that are aimed at teaching students the importance of computer-based analysis of complex systems. These enhancements also aim to provide students with preparation for professional practice by instilling in them the skills needed for using modern engineering tools, specifically in the machine design process. This was accomplished by developing analysis-based projects that students code in a math computational program (typically MATLAB). Three of these projects were carried out throughout the semester in conjunction with an introduction to the design philosophy presented by the textbook by R.L. Norton [1]. The following manuscript (1) describes the rationale for the introducing the projects, (2) gives detail description of the projects and (3) assesses the efficacy of the projects to achieve the objectives through results obtained from a survey given to students during their senior capstone design course.

1. Introduction and Background

Machine design is a required course for all nationally accredited mechanical engineering undergraduate Bachelors of Science degrees. The course typically occurs during student's junior year, and serves as the key link between the engineering mechanics course sequence consisting of statics, dynamics, and strength of materials with the capstone project course for senior students. A conventional machine design class can be separated into two main themes: design analysis and machine synthesis [1, 2]. Design analysis involves calculating physical quantities such as induced stresses, deformation, and fatigue life using theoretical and empirical equations, tables, and graphs given either component dimension, external loads, internal mass and kinematic motions. Machine synthesis involves choosing and sizing proper machine elements having certain final design specifications. This involves having a working knowledge of machine elements such as linkages, bearings, gears, springs, screws and fasteners, shafts, and columns. Over the years, the machine design course has been improved with efforts to introduce project-based learning [3], hands-on machine design laboratories [4] and finite element analysis projects [5].

Despite advances in overall curriculum, junior-level machine design course delivery has not changed much from authoritative lecture style in the classroom, together with homework assignments that only reinforce analysis concepts by solving problems through plugging explicitly given parameters in the problem statement into recently learned equations. Although the students develop a decent understanding of the theory, they struggle when given problems with ambiguous or open-ended solutions and have trouble when trying to analyze multiple design parameters in an analysis, where hand calculations can become tedious. This leads to understanding of the analytical models, but does not equip students to make appropriate assumptions for that model; also, they cannot handle uncertainty and ambiguity in the design. Overall this results in student frustration and disengagement from the course.

In engineering practice, only some of an engineer's time is spent executing analyses that have been pre-packaged. More often than not, the engineers find themselves in the position of performing an analysis that is different from those done previously. Hence, there is a great need for students to learn how to comprehensively program software to solve machine design problems because it allows them to simultaneously consider multiple design considerations. While there are current practices utilizing computational tools in a machine design course, most of the student interaction with the program is where the students only needs to input initial design parameters, and all other design calculations are performed within a program [6]. Therefore, it would be beneficial to teach students how to implement their theoretical understanding into an analysis and by doing so, the fundamental theories and concepts are not marginalized.

The objective of introducing the MATLAB projects was to encourage young mechanical engineers to enhance their programming skills, because modern day engineers need software programming skills to be successful and have a professional edge in industry. The goal of the projects was to provide a platform for improved understanding of machine design and emphasize the importance of programming in mechanical engineering, specifically (1) the fast speed at which complex problems can be analyzed and (2) the ability it provides students to be able to develop creative solutions. Such skills are expected to empower students to solve more challenging open-ended and/or integrated design problems, and to conduct design projects for a more rewarding experience in machine design. This will prepare students for a career of technical excellence in a complex, competitive and technological environment.

2. Design Project Descriptions

Three practical short design projects were introduced. These were implemented in order to provide small-scale, highly mentored problems to introduce the design process and to provide continuation of the use of modern engineering tools (e.g. MATLAB, excel, etc.). Each project took the students nominally three weeks to complete. The following projects were implemented:

Project 1 – Introduction to Design and Design Factors

For the first project, students were given a scenario with two crates, each with different masses (1,000 kg, 2,000 kg), and different size diameter of cables that could be used (varying from 10 mm to 30 mm). A picture of the scenario is given in Figure 1. Students were ask to investigate how various combinations of weight and diameter effect the distance from the ceiling that the boxes could be supported. The goal of the assignment was to design the diameter of cable that will be able to support the crates as close to the ceiling as possible but not violate a safety factor of 3. Since there were multiple factors to investigate, the analysis required students to code in a math computational program (typically MATLAB) in order to analyze the problem. Then students were required to prepare a formal report documenting their analysis, including a discussion on their results, observations, and comments pertaining to utilization of the plots by a design engineer (see supplemental section S.1 for full project description).

The purpose of this design project was to give students an opportunity to compute the distribution of safety factor over a changing design parameter, and make engineering decisions based on the information obtained. For this project students were expected to use concepts they learned in previous classes (specifically statics, solid mechanics and computational methods).

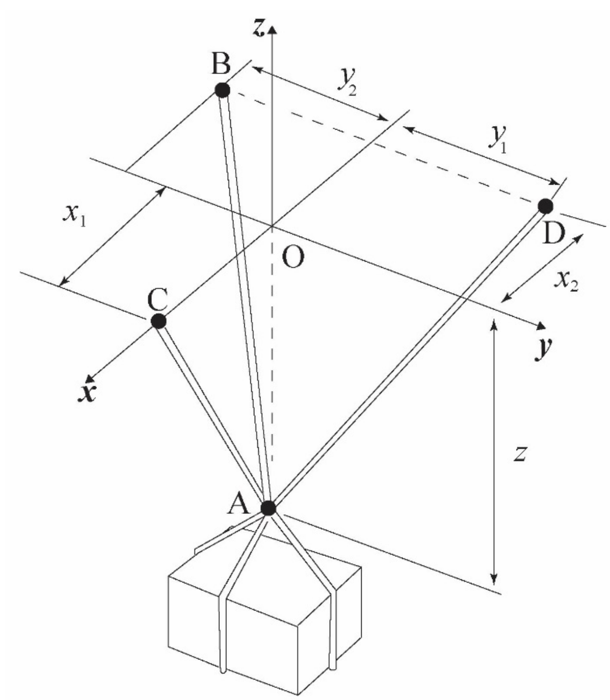

Figure 1: Picture of scenario for Design Project 1 showing a crate supported by three cables.

Project 2 – Kinematics of a Linkage System

The second design project involved a kinematic analysis of a linkage system. The project was done in the context of the practical application of an umbrella arm seen in Figure 2 and

Figure 3 [7]. The analysis requires students to code the 6-bar linkage mechanism to evaluate the position, velocity and acceleration of the various joints. Then, the students were required to prepare a formal report documenting their analysis, including a discussion on the correctness of their results and comments pertaining to the function of the mechanism (see supplemental section S.2 for full project description).

The purpose of this design project was to give students an opportunity to compute the displacements, velocities, and accelerations, of a linkage system and use modern engineering tools to reduce analysis time. For this project students used concepts they learned in class, specifically fundamental theory of linkage kinematics.

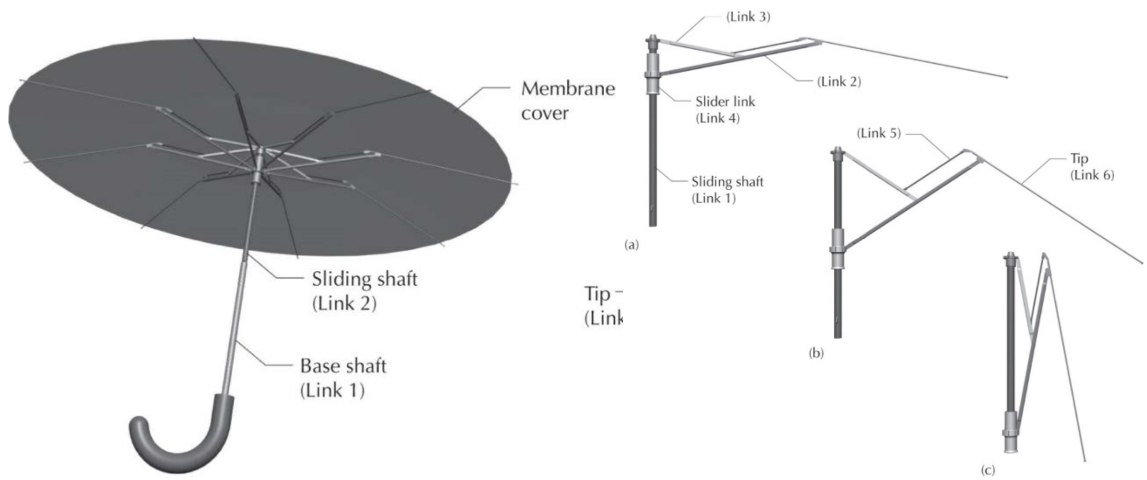

Figure 2: Picture of scenario for Design Project 2 and 3 showing at right an umbrella device and at left a single linkage of umbrella from fully open to closed: (a) Fully open, (b) partially open (c) fully closed [7].

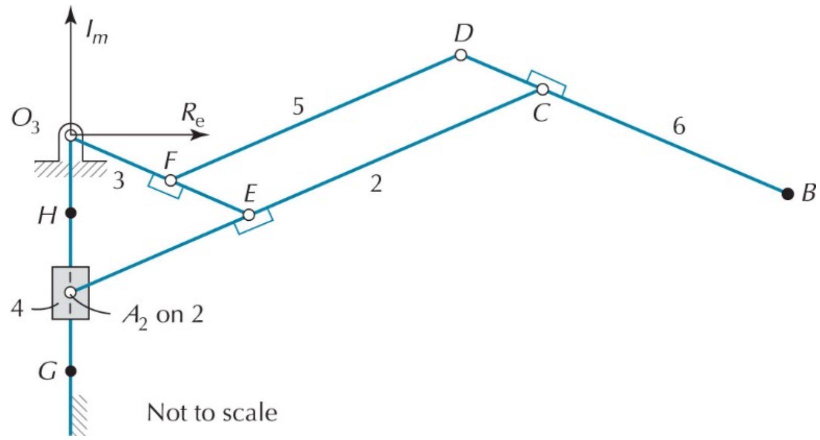

Figure 3: Picture of scenario for Design Project 2 and 3 showing the mechanism used in a folding umbrella expressed as links with joints A thru H and O_3 [7].

Project 3 – Force Analysis of a Linkage System

The third design project was an extension of the umbrella linkage system from Project 2. It required the students to code both a static and dynamic force analysis of the umbrella arm. When the umbrella opened, they needed to evaluate the various loads on the joints for given changing speed of umbrella slider and prepare a formal report documenting their analysis. The discussion needed to include the correctness of their results and comments pertaining to how changing the time in which the slide occurs affects the force analysis performed on the mechanism (see supplemental section S.3 for full project description).

The purpose of this design project was to have students be able to compare and see how the speed at which a machine part moves affects the forces on the system and the type of analysis that is appropriate to conduct. Namely, when is it okay to perform static force analysis versus dynamic force analysis? For this project students used concepts they have learned, such as linkages, force analysis, both static and dynamic.

3. Instructor Materials

The projects can be performed with a number of computational softwares such as Maple (Waterloo Maple Inc, Waterloo, Ontario), Mathematica (Wolfram Research, Champaign, IL), TK Solver (Universal Technical Systems, Inc, Loves Park, IL), etc. To date, the computational programming has been performed, primarily in the software MATLAB (MathWorks, Natick, MA). Students should be nominally separated into teams of no more than 4 (2-3 students per group is ideal).

4. Discussion and Student Outcomes

The projects were performed successfully in a machine design course in the spring of 2016 with sixty-five junior mechanical engineers, both male and female. During the fall of 2016, a survey was given to the same students, who were now seniors, at the end of the first semester of their capstone senior design sequence. Fifty-nine survey responses were returned for examination. Students were ask to gage how helpful the projects were in furthering their knowledge based on the goal of the projects. The efficacy of the projects were determined through the results obtained from the survey. The results can be used to adjust and strengthen the projects for future classes.

From the results of the questionnaire (see Supplemental Section S.4), two major conclusions were drawn; the goals of including the MatLab projects into the course were met and that overall the students found the projects a positive experience. The summary of the results can be seen in Table 1.

Table 1: Percentage (%) of student at each ranking level for each question.

Rankings*	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6
1	0%	3%	0%	2%	7%	8%
2	3%	5%	15%	15%	25%	19%
3	63%	42%	64%	42%	41%	32%
4	25%	44%	15%	34%	24%	27%
5	8%	5%	5%	7%	3%	14%

* = see supplemental section S.4 for meaning of rankings and questions.

Overall, students found the pace and schedule of the projects somewhat elevated with an average score of 3.39 ± 0.70 out of 5, with 1 being rated as “much too slow/lagged behind material taught in class”, and 5 being rated as “much too fast/had to accomplish them before we were taught class material”. However the majority of the students, 63% rated the pace of the projects as a 3 being rated as just right/stayed with material taught in class. This result suggests that the schedule for the projects, giving the students two weeks to complete one project, is a sufficient period for students to properly complete each assignment.

The students described the level of difficulty of the projects the difficulty level slightly higher than acceptable with an average of 3.42 ± 0.81 out of 5, with a rating of 1 being “much too easy”, 3 being “just right” and 5 being rated as “much too hard”. The class was relatively split on this question, with 42% of students rating the difficulty a 3 and 44% of the students rating the difficulty of the projects a 4. Significantly fewer students rated the projects as easy (8%) or extremely hard (5%). This was an encouraging result, because having a low number of students rate this question a five showed that from the students perspective the projects were achievable. This was promising, because as long as the students found them achievable they would not lose motivation to complete them. This, coupled with the fact that almost every response considered the assignments difficult or slightly above means that our projects were at the proper difficulty level.

Student were asked to reflect on how intellectually stimulating the MatLab projects were, with a rating of 1 being “not very stimulating”, a rating of 3 being “just right” and 5 being “too much”. The overall results were mediocre, with an average score of 3.10 ± 0.71. We believe this is because students equate intellectual stimulation with difficulty. Intellectual stimulation is defined as being encouraged to innovate and be creative, as well as encouraged to critical think and problem-solve. Intellectual stimulation involves arousing students’ thoughts and imagination [8]. However students tend to think that more thought means more work and thus an increased level of difficulty. When comparing the results of asking students about the difficulty level of the class and how intellectually stimulating the projects were, the student ratings were very similar (Table 1), with 64% of students rating the projects as just right for intellectual stimulation and 63% rating the course for just right difficulty level.

The goals of the projects were to (1) provide a platform for improved understanding of machine design while emphasizing the importance of programing in mechanical engineering, (2) teach students that using computational program would allow them to solve complex problems with increased speed, and give them the ability to be able to develop creative solutions so that (3) they would be motivated to increase developing their programming abilities. Forty one percent of the students rated the projects as being helpful or extremely helpful at showing them the fast speed at which complex problems can be analyzed, with the average rating being (3.29 ± 0.87 out of 5). Only 27% percent of students stated that the Matlab projects provided them with the ability to be able to develop creative solutions for design problems. This result displays that there is room for improvement. Namely, to develop more projects that are open-ended where the students are able to develop solutions that are more creative. The addition of another project with that specific goal would be beneficial (see Future Work section). Finally, 75% of students reported that the Matlab projects somewhat motivated them or extremely motivated them to increase development of their programming abilities. This was a very exciting result as it shows that the project are reaching their intended goals.

One limiting factor which affects the projects is the number of students per team. This is a concern because increasing the number of students leads to a number of things, most important being a decrease in student engagement in the coding of the project. The ideal maximum student number per team for the projects is three, because with more than three team members there becomes more of an opportunity for a student to disengage in participating in the coding and offer to complete some other aspect of the project (for example: just write the reports). With three students per team, the workload is more evenly shared and each student takes ownership for his or her learning.

In conclusion, the students appreciated the coding opportunities that the projects provided. Working together in small groups encouraged the students to discuss the codes and results. From the results of the questionnaire, it was evident that an improved understanding of machine design was successfully tied into design-based projects, while simultaneously emphasizing the importance of programing in mechanical engineering.

5. Future Projects

It would be beneficial to add one more programming Design Project. This project will focus on uncertainty and ambiguity in the design and analyzing multiple design parameters in an analysis. One idea for this project is to investigate the dimensional and material design of a simple machine such as a pair of ice tongs. In the project, students would be given initial geometry of the system along with the weight and dimensions of blocks of ice. Students would be asked to design the tongs for cases of static failure and fatigue failure, investigating different cross sectional areas and multiple material properties, including ductile and brittle materials. Students would use concepts they have learned in classes such as curved beam mechanics, principle stress analysis, von Mises and Coulomb-Mohr effective stresses, as well as fatigue failure theories.

Supplemental Information

S.1: Example of Project 1 Description

Syracuse University **Mechanical and Aerospace Engineering**
MEE 332 **Spring 2016**

Design Project #1

Introduction to Design and Design Factors

Due Friday February 5, 2016 at 2:15pm

Introduction: The purpose of this design project is to give you an opportunity to compute the distribution of safety factor over a changing design parameter, and make engineering decisions based on the information you obtain. For this project you will use concepts you have learned in previous classes (specifically statics, solid mechanics and computational methods). This project is due two weeks from today, and is to be handed in during Laboratory 3.

Project Description: A crate is hanging from a ceiling and is being supported by three cables, each of equal diameter (*d*) made from a 2024 annealed Aluminum. The initial positions of the cables are as shown in Figure 1, but the height (*z*) at which the weight sits a distance from the ceiling can be varied.

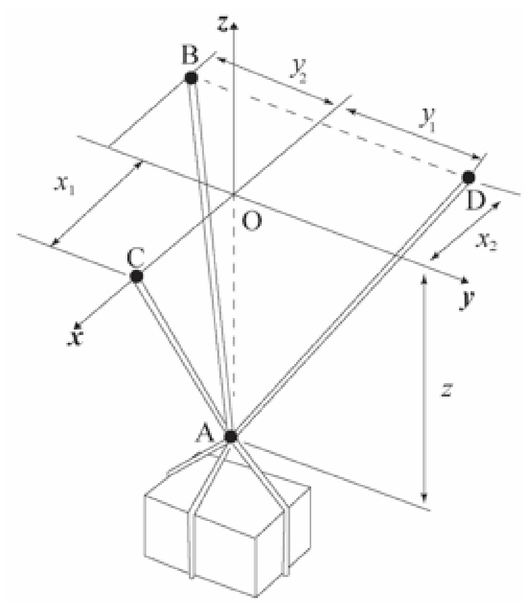

Figure 1: Crate supported by three cables.

You have two varying sizes of crate, each with different masses (m_1 = 1,000 kg, m_2 = 2,000 kg), and you have different size diameter of cables that could be used (varying from d = 10 mm to 30 mm). You are going to investigate how various combinations of weight and diameter effect the distance from the ceiling that the boxes can be supported, with the goal of designing the diameter of cable that will be able to support the crates as close to the ceiling as possible but not violating a safety factor of 3. To start off, let x_1 = 3.2 m, x_2 = 2.7 m, y_1 = 4.0 m, y_2 = 3.6 m.

You can do this by writing a program to:

- Establish a relationship between distance between the box and the ceiling and the tension in the cables. (I would start with 0.01 m $\leq z \leq$ 6 m).
- Develop a plot of design factor (loss-of-function/maximum allowable parameter) versus the changing height in the box.

Laboratory #1 Report Requirements:

Once you have accomplished the above tasks, generate a maximum 5 – 8 page Project Report that contains:

1. An introduction to the project (a paragraph is sufficient).
2. An analytical procedure for the solution to the problem. Follow the format below in order to give a description walking through the main principles and equations.
    - Definition of the problem (include a figure)
    - State the givens
    - Make the appropriate assumptions
    - Explain mathematical models that will be used in the solution
    - Develop a procedure for analysis of the problem
    - Brief explanation of anticipated results
3. A plot containing the change in force for each of the cables versus the change in height. Make sure the plot is properly labeled (x-axis label, y-axis label, title, grid)
4. A plot containing the safety factor versus the change in height. Make sure the plot is properly labeled (x-axis label, y-axis label, title, grid)
5. A discussion of your plots, where you explain what you plotted, any observations you have (such as, "The maximum point is at…" "There are singularity points at…"), along with how this plot can be utilized by a design engineer (such as "by reading this plot we can see that the ideal diameter and mass combination is… because…"). You can include supplemental plots in order to enhance your discussion.

S.2: Example of Project 2 Description

Syracuse University **Mechanical and Aerospace Engineering**
MEE 332 **Spring 2016**

Design Project #2

Kinematics of a Linkage System

Due: Friday February 19, 2016 at 2:15pm

Introduction: The purpose of this design project is to give you an opportunity to compute the displacements, velocities, accelerations, of a linkage system. In subsequent projects, you will compute the forces for the system based on given specifications. For this project you will use concepts you have learned in classes (specifically linkage kinematics and position dynamics).

Project Description: Figure 1 shows a schematic of a folding umbrella. The modern folding umbrella is constructed of a linkage system designed to deploy a canopy used to protect against rain or sunlight; the mechanism allows the folded umbrella to be more compact than would be possible with a simpler folding mechanism. Figure 2 shows an umbrella with the membrane cover removed to reveal the mechanisms employed to deploy the membrane. The umbrella is brought from a closed to an open position by moving the slider upward. A schematic of a similar mechanism is illustrated in Figure 3. The slider can move upward with respect to the sliding shaft to move other links of the umbrella upward and outward during use.

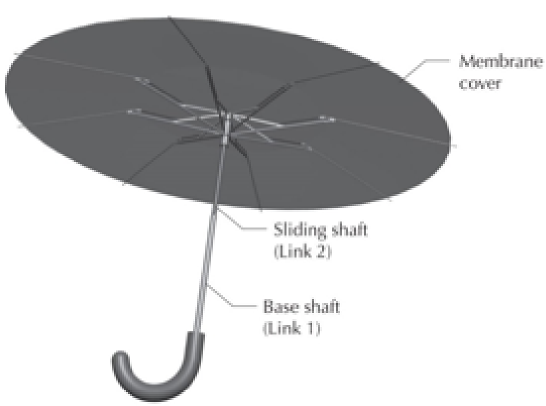

Figure 1: An umbrella device.

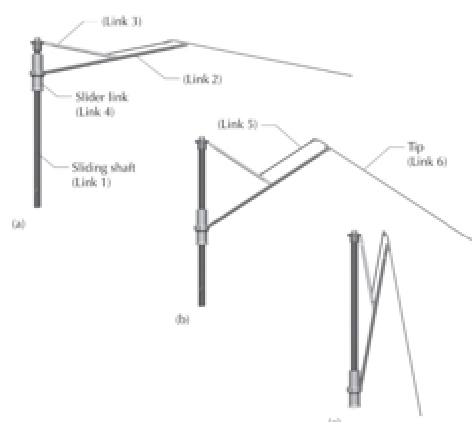

Figure 2: Single linkage of umbrella from fully open to closed: (a) Fully open, (b) partially open (c) fully closed.

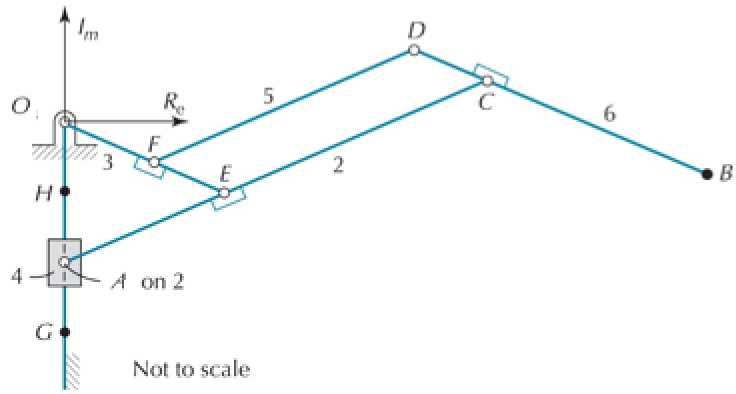

Figure 3: Mechanism used in a folding umbrella

This mechanism is composed of a slider, A, that rides on vertical shaft GAHO. There are four bars: AEC, OFE, DCB, and DF. To start with, use the following lengths:

$$r_{AE} = 16.0\ cm$$
$$r_{AC} = 29.0\ cm$$
$$r_{OF} = 13.0\ cm$$
$$r_{OE} = 16.0\ cm$$
$$r_{DC} = 3.0\ cm$$
$$r_{DB} = 35.0\ cm$$
$$r_{DF} = 13.0\ cm$$

Even though some of the dimensions are the same, you should not expect this to always be the case. You can determine the coordinates of the points of each link as a function of the position of A, which is given as a function of time by:

$$x_A = 0$$
$$y_A = -17.5 - 12.5\cos\left(\frac{\pi t}{\tau}\right) cm$$

where the opening time is $\tau = 2.0\ s$.

Once the positions are found, the velocity and acceleration can be found. (Note: you do not need to use vector loop to solve this system, position dynamics will work as well.)

Laboratory #2 Report Requirements:

Generate a maximum 5 - 8 page write up that contains at least the following:

1. A short introduction to the project (a paragraph is sufficient).
2. An analytical procedure that describes what you did for the solution to the problem.
3. Plots containing:
    a. Trajectory at each joint
    b. Velocity at each joint versus time
    c. Acceleration of each joint versus time

   Make sure the plot is properly labeled (x-axis label, y-axis label, title, and grid).
4. A discussion of your plots: what the various plots show, any observations you have (such as, "The maximum point is at…"), along with how this plot can be utilized by a design engineer (such as "by reading this plot we can see that the trajectory of position B is… because…" or "we can use this plot to understand…")

S.3: Example of Project 3 Description

Syracuse University | **Mechanical and Aerospace Engineering**
MEE 332 | **Spring 2016**

Design Project #3

Force Analysis of a Linkage System

Due: March 4, 2016 at 2:15pm

Introduction: In last week's project you computed the kinematic analysis of a planar mechanism which involved the position analysis, followed by the velocity analysis and then the acceleration analysis. Now you will compute the subsequent forces for the system based on given specifications. For this project you will use concepts you have learned in classes (specifically linkage kinematics and force dynamics).

Project Description: As a reminder, Figure 1 shows a schematic of the mechanism of a folding umbrella. The slider can move upward with respect to the sliding shaft to move other links of the umbrella upward and outward during use.

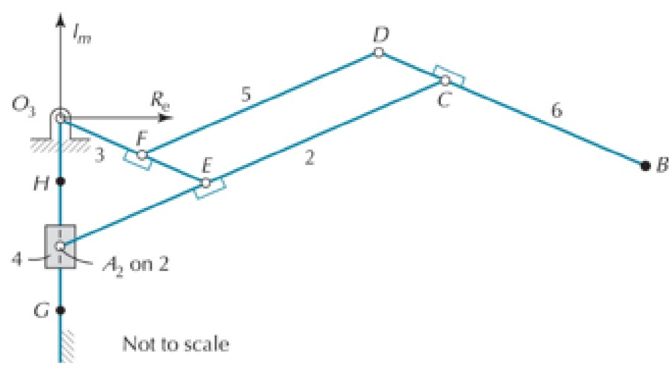

Figure 1: Mechanism used in a folding umbrella

Using the dimensions and joint position functions from Design Project 2, calculate the forces at each of the joints for various opening times (τ) if a weight of 2.0 kg is hung from point B and the bars in the mechanism all have a mass of 0.1 kg/cm. Opening times will vary from slow to fast ($\tau = 0.02\ s,\ \tau = 0.2\ s, \tau = 2\ s, \tau = 20\ s,\ \tau = 200\ s$).

Design Project 3 Report Requirements

Generate a maximum 5 - 8 page write up that contains at least the following:

1. A short introduction to the project (a paragraph is sufficient).
2. An analytical procedure that describes what you did for the solution to the problem.
3. Plots containing:
    a. Force at each joint over time for $\tau = 0.02\ s$
    b. Force at each joint over time for $\tau = 0.2\ s$
    c. Force at each joint over time for $\tau = 2.0\ s$
    d. Force at each joint over time for $\tau = 20\ s$
    e. Force at each joint over time for $\tau = 200\ s$

   Make sure the plot is properly labeled (x-axis label, y-axis label, title, and grid). Note: you need to have the correct trajectory, velocity and acceleration of each joint before you complete your force analysis.
4. A comparison and discussion of your plots: what the various plots show, any observations you have about how changing the time in which the slide occurs affects the force analysis performed on the mechanism.

S.4: Survey given to seniors students who took machines design in spring 2016.

MEE332 EVALUATION SHEET
MATLAB Design Projects

Please indicate the semester you took MEE332: ______________________

Please answer the following questions by circling the number (1-5) that best describes your thoughts.

1. How would you describe the pace and schedule of the MatLab projects?
(1 = much too slow/lagged behind material taught in class, 3 = just right/stayed with material taught in class, 5 = much too fast/had to accomplish them before we were taught class material)

1	2	3	4	5

2. How would you describe the level of difficulty of the MatLab projects?
(1 = much too easy, 3 = just right, 5 = much too hard)

1	2	3	4	5

3. How would you rate the intellectual stimulation you received from the MatLab projects?
(1 = not enough, 3 = just right, 5 = much too much)

1	2	3	4	5

4. Please rate how helpful the MatLab project were at showing you the fast speed at which complex problems can be analyzed.
(1 = not at all. 3 = somewhat, 5 = extremely)

1	2	3	4	5

5. Please rate how well the MatLab projects provided you with the ability to be able to develop creative solutions for design problems.
(1 = not at all. 3 = somewhat, 5 = extremely)

1	2	3	4	5

6. Please rate how much the MatLab projects motivated you to increase development of your programming abilities.
(1 = not at all. 3 = somewhat, 5 = extremely)

1	2	3	4	5