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Utilizing Computational Tools to Enhance Student's Understanding of Linkage Mechanism

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Abstract

This research presents analysis of a quick return linkage mechanism utilizing computational software Mathcad and Inventor. It is implemented as a class project to enhance Mechanical Engineering and Mechanical Engineering Technology students' understanding of linkage mechanism in courses Dynamics and Machine Dynamics. The objectives of the project are to teach (1) kinematic and kinetic analysis of linkage mechanism (2) engineering math software Mathcad to solve the analytical model, (3) verifying the model by multibody dynamics simulation software Inventor. Loop closure equations based on complex number are first modeled and solved to find positions, velocities and accelerations of the linkage in Mathcad. Based on the kinematic solution, a kinetic analysis is carried out using distributed mass models in Mathcad as well as in Inventor simulation. The output slider position and the input link torque are found identical to simulation results with negligible deviation. Integrating industry commonly used software Mathcad and Inventor in the project reduces the mathematical difficulties often encountered by engineering students. The course project assignment grade demonstrates that the use of these tools enhances the student's understanding for linkage mechanism. The feedback from instructors shows the project make the course dynamic and machine dynamics more engaging. The software-based project suits well for online teaching and learning.

Keywords:

Linkage, Kinematics, Kinetics, Mathcad, Inventor

1. Introduction

Linkage quick return mechanisms are using linkage to convert rotation motion input into reciprocating motion output. And the forward stroke of the reciprocating slider is slower than the backward stroke. The typical applications include metal shapers, press machines which prefer slow speed high load working stroke and high speed low load return stroke to improve efficiency [1]. Quick return linkage mechanism synthesis and analysis is covered in Mechanical Engineering (ME) or Mechanical Engineering Technology (MET) programs' junior year course Machine Dynamics [2].

Teaching linkage kinematics and kinetics very often present challenges for the instructors due to the mathematical difficulties and the students' lack of understanding of the mechanism [3, 4]. Matlab and Excel program has been used to help students analyze linkage mechanism [5]. 3D modeling and printing labs have also been developed to improve the teaching quality and students' understanding [6]. Reference [7] designs the linkage mechanism for robot gripper as capstone projects.

In this study, Mathcad and Inventor Dynamic Simulation is used to solve for the kinematic and kinetic quantities of a six bar Whitworth linkage mechanism as a class project for Dynamics and Machine Dynamics. At Miami University, the project is used for MET Dynamics course with emphasis on using the software and result interpolation to help student visualize linkage mechanism. At Penn State Behrend, the projects described in this work were assigned to ME students in the Machine Dynamics and completed within the first eight weeks with the course lectures. After completing these projects, students should be able to: (1) analyze the kinematics of planar linkage mechanisms, (2) use Mathcad programs to solve complex machine dynamics problems or systems, (3) model and simulate linkage mechanism in Inventor. Our previous study [8] showed that introducing practical applications to students is beneficial to their comprehension and engagement. Similar conclusion can be drawn for this paper from the student project grade and instructor survey. The complete solution to the mechanism, including course syllabi, the Mathcad scripts, and CAD files will be provided for educators to modify and tailor for specific needs. The models can be adopted by the engineering courses covering planar linkage mechanisms projects.

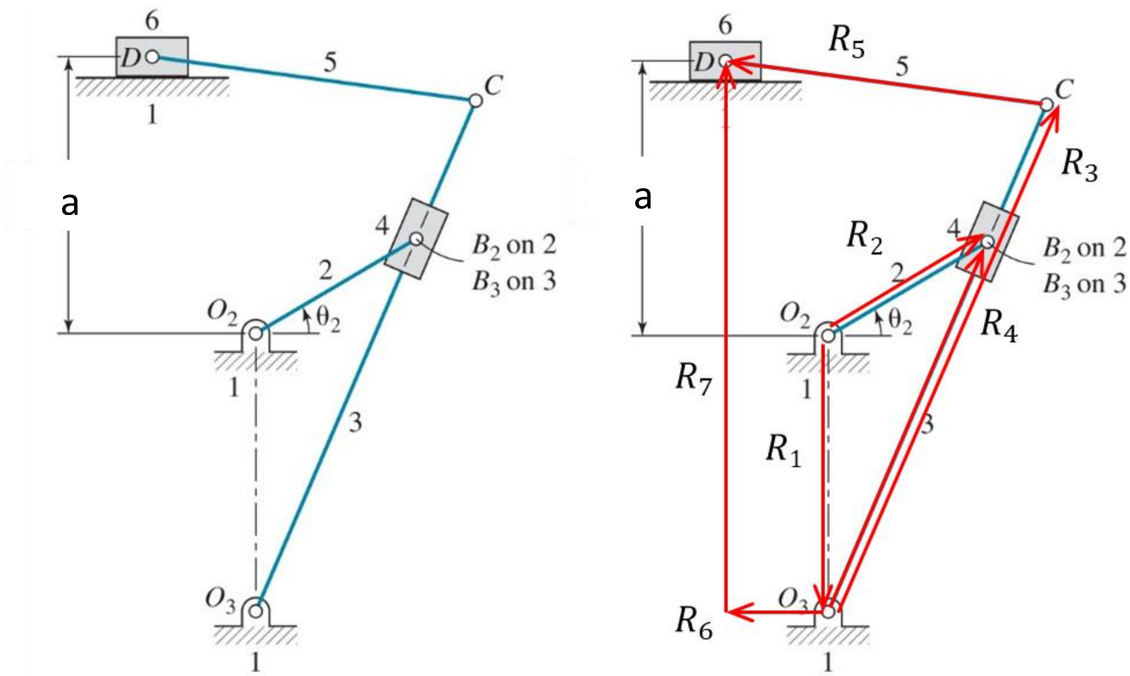


Figure 1. Kinematic diagram

2. Project Description

The Whitworth quick-return mechanism is shown in Figure 1. The planar linkage has six kinematic links and seven kinematic joints with one degree of freedom [9]. Link 3-4 and 1-6 are prismatic joints (sliders). The rest are rotational joints. Since the mechanism has one degree of freedom, the kinematic quantality including position, velocity, and acceleration of the linkage can be calculated from input crank link 2's position and angular velocity and acceleration by kinematic analysis. The forward and backward time ratio can be calculated from Equation (1).

If an external force acts on link 6 slider, other links' reactions and the input toque on the crank can be found by kinetic analysis.

$$T_R = \frac{\pi - \arccos\left(\frac{r_2}{r_1}\right)}{\arccos\left(\frac{r_2}{r_1}\right)} \qquad (1)$$

3. Kinematic and Kinetic Analysis and Verification

Kinematic analysis uses loop closure equation method [10]. Two kinematic loops are built. The first loop consists the ground 1, input crank 2, and the slider 4, and the second loop includes the output slider 6, rocker 3, and connecting rod 5 as shown in Figure 1, loop closure equations can be modeled as,

$$\boldsymbol{R_2} = \boldsymbol{R_1} + \boldsymbol{R_4} \qquad (2)$$

$$\boldsymbol{R_3} + \boldsymbol{R_5} = \boldsymbol{R_6} + \boldsymbol{R_7} \qquad (3)$$

Equation (2) and (3) are vector equations with $\mathbf{R_n}$ as complex numbers [10].

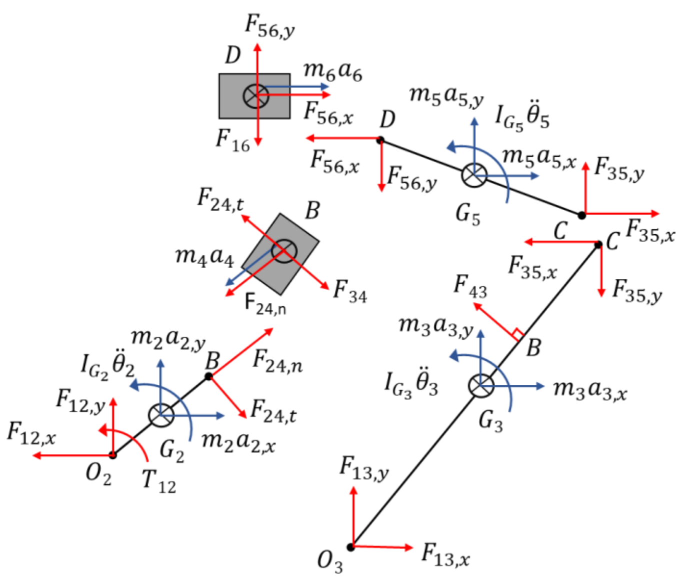


Figure 2. Kinetic diagram

The kinematic analysis including position, velocity, acceleration and kinetic analysis for joint forces in Mathcad is attached as google drive shared file with link in Appendix.

The kinetic model is based on distributed mass kinetic model [2] as show in Figure 2.

The numerical example of the mechanism was simplified from a Cincinnati Metal Shaper, which uses linear motion between the workpiece and a single-point cutting tool to machine a linear toolpath, as shown in Figure 3. The scaled lengths of the links are $r_{O_2O_3}$ = 12 in, $r_{O_2B_2}$ = 8 in, r_{O_3C} = 24 in, and r_{CD}= 14 in. All links were assumed the same density $\rho = 10$ lbm/in, and the sliders 4 and 6 have the same mass as link 2. The vertical distance of the pivot O_2 to the path of the slider 6 is a=12 in. The input angular velocity of the crank 2 is $\theta_2 = 20\ rad/s$.

With the given parameters, the linkage mechanism is modeled and assembled in Inventor as shown in Figure 4. The input angular velocity is setup in Dynamic Simulation module.

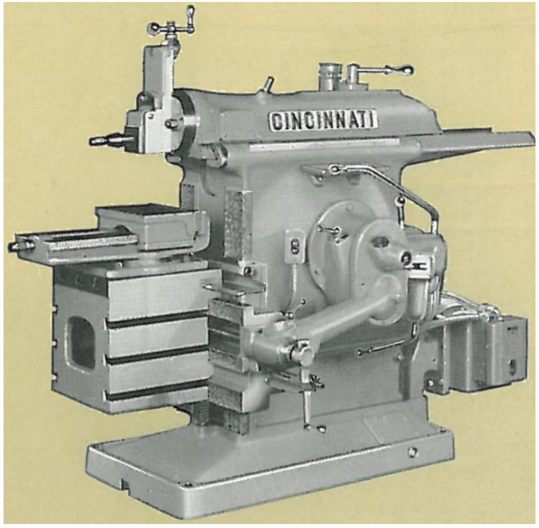


Figure 3: Cincinnati Metal Shaper

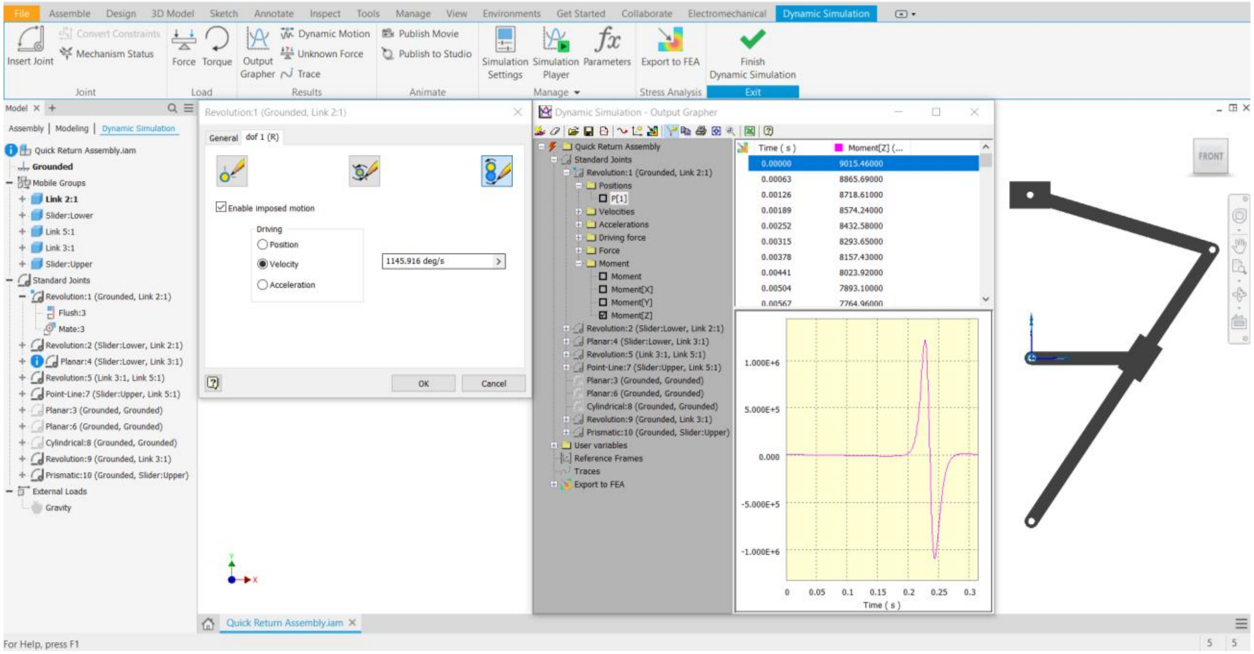
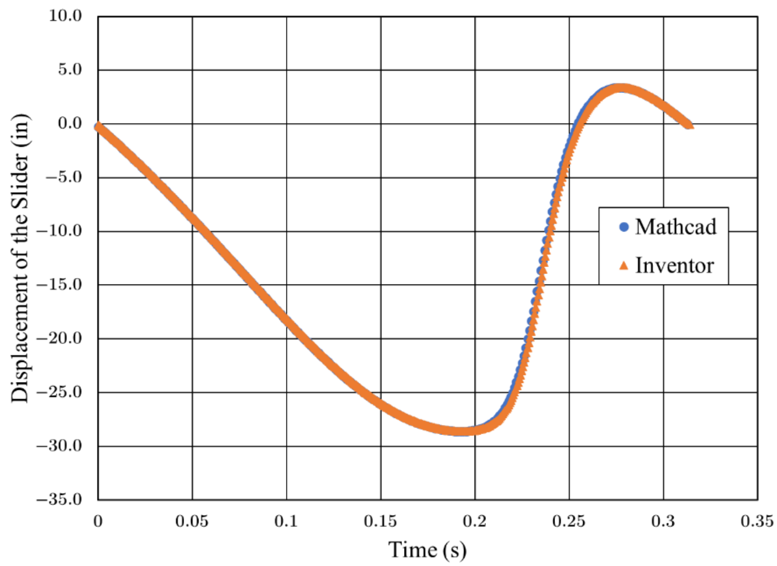
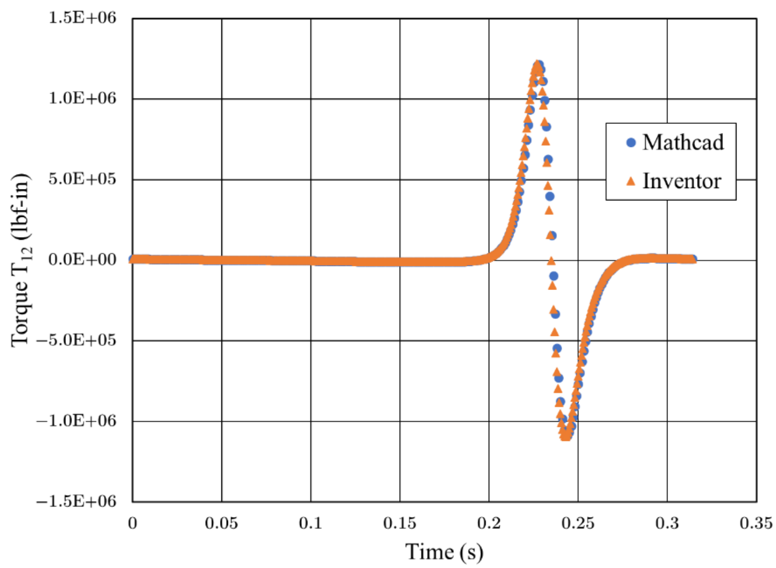


Figure 4. Inventor Dynamic Simulation Model

To verify the analytical and simulation result, the slider position and input torque is shown in Figure 5. The analytical results from Mathcad and simulation result from Inventor are identical with deviation within 3%. Complete kinematic and kinetic analysis results can be found from Appendix.



(a)



(b)

Figure 5: (a) Positions of the slider 6 and (b) input toque on the crank 2.

4. Student Grade Analysis

A pilot engineering education study has been implemented in two summer session Dynamics course, and three semesters Machine Dynamics course.

In Dynamics, student teams will be offered with the analytical solution in Mathcad with the project description. The project emphases on the student's ability to establish the 3D model and conduct dynamics simulation in Inventor, and then verify simulation results with analytical results. The feedback from the instructors' course survey is positive and the average students course grade improved from 87.8 to 90.5 comparing two consecutive summer semesters. To improve the statistical significance of the project's impact on students, more data are currently being collected for future study. The project grade has been used to support the ABET's MET AS program outcomes [11].

(1) an ability to apply knowledge, techniques, skills and modern tools of mathematics, science, engineering, and technology to solve well-defined engineering problems appropriate to the discipline;

(2) an ability to design solutions for well-defined technical problems and assist with the engineering design of systems, components, or processes appropriate to the discipline;

(3) an ability to apply written, oral, and graphical communication in well-defined technical and non-technical environments; and an ability to identify and use appropriate technical literature

(5) an ability to function effectively as a member of a technical team.

Two projects including Project 1 kinematic analysis and Project 2 kinetic analysis are given to Machine Dynamics courses starting spring 2020. The student grade is shown in Figure 6. The average for project 1 in spring 2020 is 86.8, 95% students received D or above grade. The average for project 1 in fall 2020 is 78.5, 85% students received D or above grade. The average for project 2 in fall 2020 is 66.8, 54% students received D or above grade. Comparing with final exam, project 2 covers wider scope, more complex math, software skills, and report writing. Although more students failed project2, the project engaged students to spend more time for understanding linkage mechanism. It improves the students' final exam grade.

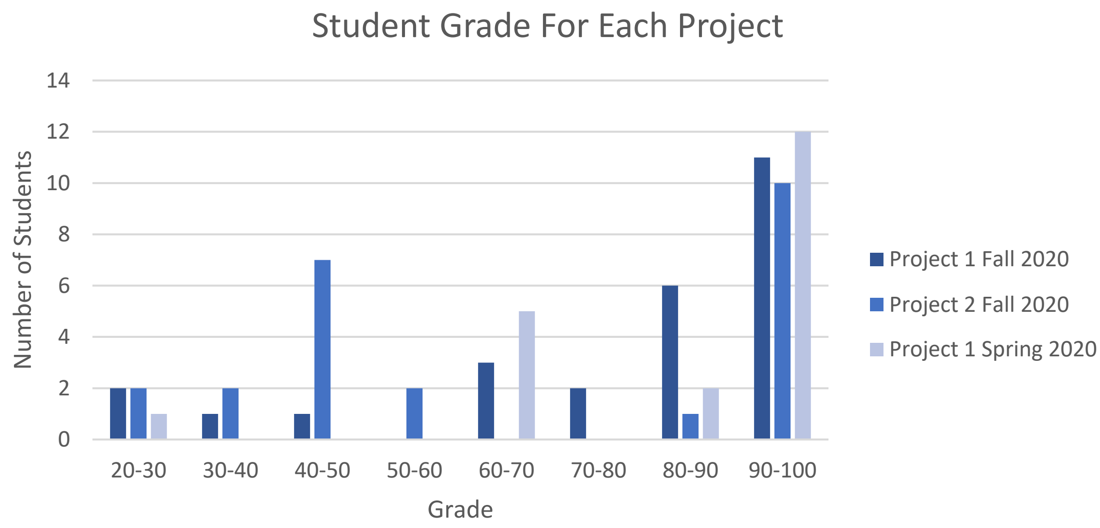


Figure 6. Student Grade for Each Project in Different Semester

Compiled student grade for Machine Dynamics class is shown in Figure 7. The average score is 76.9 with 24.8 deviation. 77% students received D or above grade.

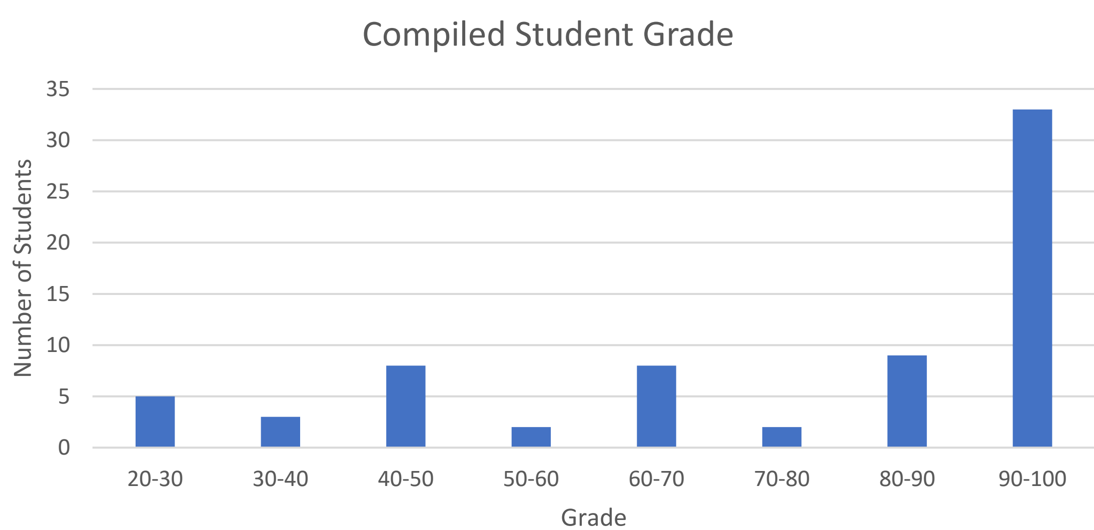


Figure 7. Compiled student project grade

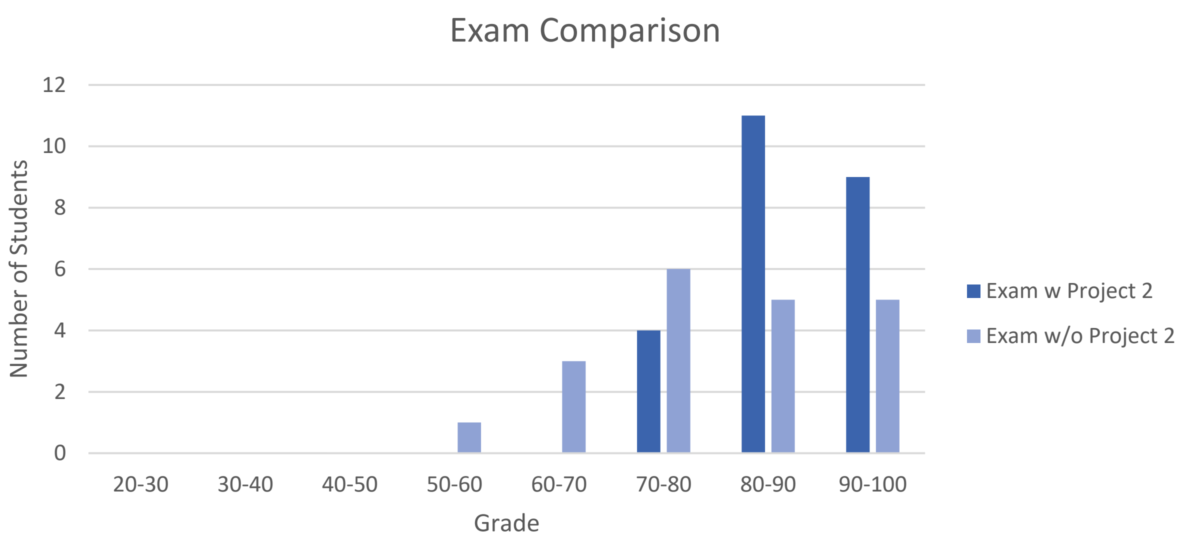


Figure 8 Exam Comparison

Figure 8 shows Spring 2020 and Fall 2020 student final exam grade. Spring 2020 does not have project 2 kinetic analysis. On contrary, fall 2020 has the project 2. The student final exam average grade increases from 82.8 to 87.6, which demonstrates the project increases the students' understanding of linkage analysis in the fall semester.

5. Conclusion

Therefore, the following conclusions can be drawn from the research.

- The linkage analytical model in Mathcad is verified by Inventor Dynamic simulation with negligible deviation.
- With the help of Mathcad and Inventor, sophomore students in Dynamics are able to model and analyze linkage mechanism and verify the models with less mathematical difficulty. It improves students understanding of linkage mechanism. The project grade feeds to ABET MET student outcomes 1, 2, 3, and 5.

- The course project assignment grade in Machine Dynamics quantitively demonstrates that the majority (77%) of the junior students are able to finished the project with the use of Mathcad and Inventor. It enhances the student's understanding for linkage mechanism with improved final exam grade.
- Most of the above-mentioned projects are launched in online learning environment. The software-based project suits well for online teaching and learning.

6. Future Work

Two semesters' Dynamic course grade and three semesters' Machine Dynamics course grade has been used for the pilot study of implementing this project. With the support from PennState Center for Teaching and eLearning Initiatives, data will be collected in the future for comparing in-person and virtual delivery.

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Appendix

Complete Kinematic and Kinetic Solution in Mathcad and CAD model Google Drive link

https://drive.google.com/drive/folders/1HFJPdUEuBvtQ7v-2_lubcJaSgTz_YsEo?usp=sharing

Course Material for Dynamics

https://drive.google.com/drive/folders/1d59oLV6TxwAm6MdxId2TZSigScFjGCOD?usp=sharing