AC 2007-1926: TEACHING DESIGN AND MANUFACTURE OF MECHANICAL SYSTEMS

William Waldron, Grand Valley State University

Pramod Chaphalkar, Grand Valley State University

Shabbir Choudhuri, Grand Valley State University

John Farris, Grand Valley State University

Teaching Design and Manufacture of Mechanical Systems Using Multidisciplinary Teams

Abstract

The goal of this work is to increase the emphasis on the *design* and *manufacture* of mechanical *systems*. To aid in this effort, Mechanical Engineering (ME), Product Design and Manufacturing (PDM) faculty in the School of Engineering at Grand Valley State University (GVSU) are collaborating with Industrial and Manufacturing Engineering faculty from Kettering University using their model for the multidisciplinary integration of interdepartmental courses. This strategy includes vertical and horizontal integration along with a just-in-time approach for component design. Students may also outsource work to other classes, e.g., finite-element analysis might be done by students in a graduate course. This allows students to collaborate with people with other specialties and be introduced to integrated system design and manufacturing. It also helps them visualize the complete system and the big picture throughout the project. Integrated or multidisciplinary teams allow learning from faculty to faculty, faculty to students, and students to students. Comparisons can be made between integrated and non-integrated teams.

Introduction

A lot of progress has been made in recent years in improving engineering education, e.g., emphasizing communication skills, working in teams, integration of computer-aided engineering (CAE), and capstone/senior design projects. Previous work by the authors has focused on improving the integration of CAE[1,2,3,4] into mechanical engineering programs. The goal of this paper is to document efforts to improve the experiences of students working in project design teams. The strategy is to create integrated project teams from machine design, product design, and manufacturing courses to design and build a wide variety of products. The authors are collaborating with faculty from Kettering University in an NSF-funded project to investigate the use of vertical (*projects with collaboration between classes at different levels but the same discipline*) and horizontal (*projects with collaboration between classes at the same level but different disciplines*) integration in student projects.

Another consideration is that machine design courses tend to be focused primarily on machine *component* design. A second goal is to increase the emphasis on the design of machine systems. To accomplish this, a just-in-time approach will be used for component design, and students may also outsource work to other classes, e.g., finite-element analysis might be done by students in a graduate course. This allows students to collaborate with people with other specialties and be introduced to integrated system design and manufacturing. It also helps them visualize the complete system and the big picture throughout the project. Integrated or multidisciplinary teams allow learning from faculty to faculty, faculty to students, and students to students. Comparisons can be made between integrated and non-integrated teams. There is also an opportunity for the administration to develop strategies for scheduling classes so that the students from each class are able to find common times to work together.

Funding provided by National Science Grant No. 0234478, Principle Investigators: Lucy King and Tony Lin, Kettering University

This paper describes the preparations and early experiences of the students. Preparations include developing the projects for the teams, the integration structure, methods for monitoring the integrated and non-integrated teams, and plans to provide outsourcing and assessment. The successes as well as what could be improved will be reviewed at the end of the project to help machine design, product design, and manufacturing students make the transition from component design and fabrication to concurrent design and manufacture of mechanical systems.

Previous Work

In Phase I during the 2006 winter semester, two sections of EGR 409 (Machine Design II) students developed solid models of mechanisms designed to raise the lower dishwasher rack to reduce pain and injury for people with physical disabilities. Teams of two students created a wide variety of designs that included motor-driven mechanisms and spring-driven designs. Some mechanisms moved the rack out and up simultaneously while others moved the rack out using gears on tracks with a separate mechanism to lift the rack. The components were designed based on strength and fatigue-life considerations. At the end of the semester, the machine design students participated in a poster session with other project-based classes, and awards were provided for the best technical design and the most innovative design. The competitions provided additional motivation for the students to do their best work[1].

Figures 1-4 show four examples of the dishwasher designs from the winter 2006 semester. The first two designs include rack and pinion systems to move the lower rack out of the dishwasher enclosure. After moving the lower rack out of the enclosure, these two designs raise the lower rack using an electric cylinder and four arms that raise the rack with spur gears, respectively. The design in Figure 3 uses a scissor mechanism to raise the rack in one fluid motion. The last design (shown in Figure 4) incorporates a four-bar linkage, wheel and track system, and is powered from below by a ball screw and electric motor. Altogether there were approximately 20 different designs last winter, but no prototypes were made.

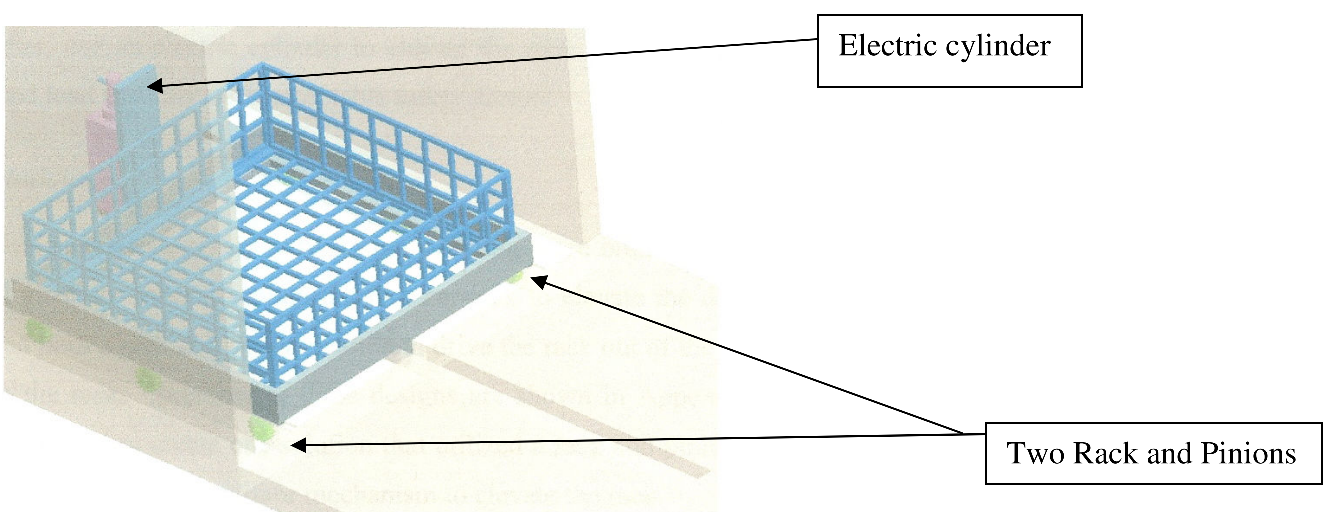


Figure 1: Lower dishwasher rack raised by an electric cylinder

Funding provided by National Science Grant No. 0234478, Principle Investigators: Lucy King and Tony Lin, Kettering University

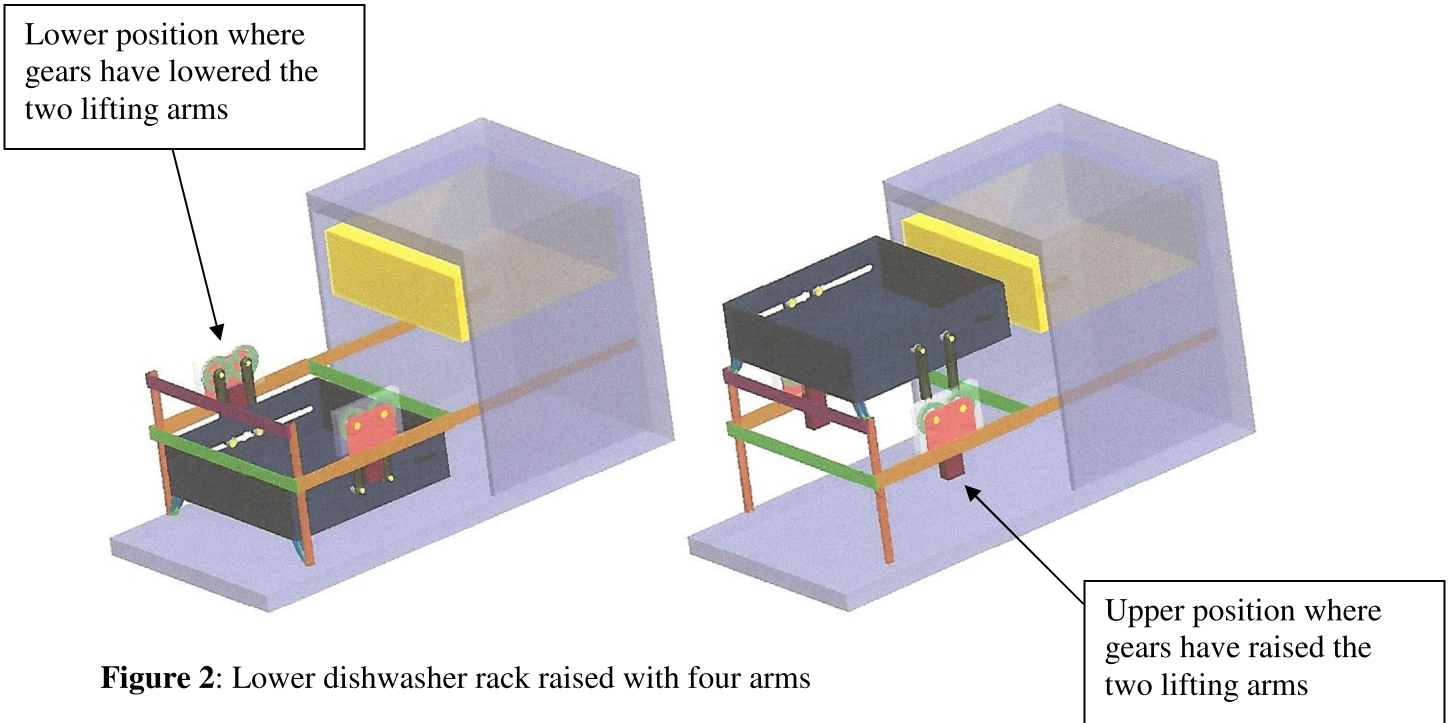


Figure 2: Lower dishwasher rack raised with four arms

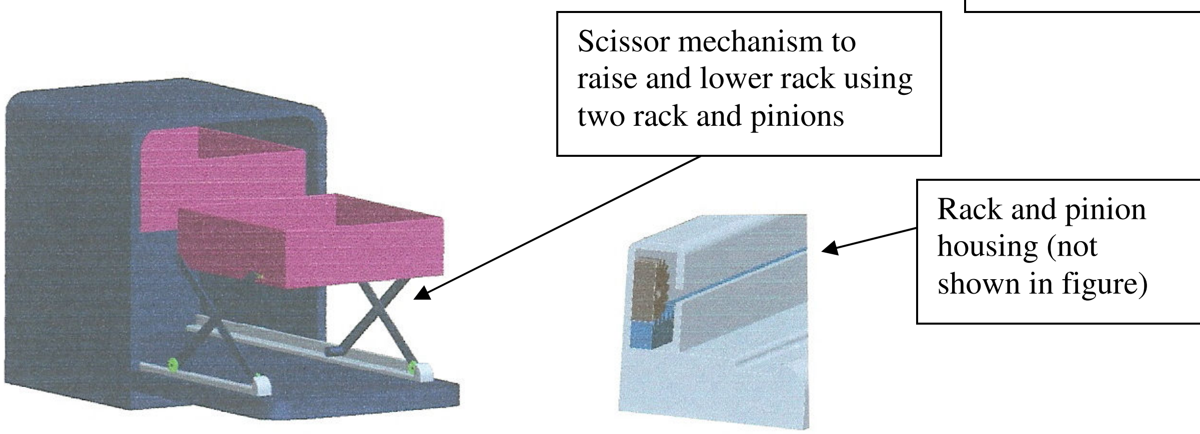


Figure 3: Lower dishwasher rack raised with scissor mechanism

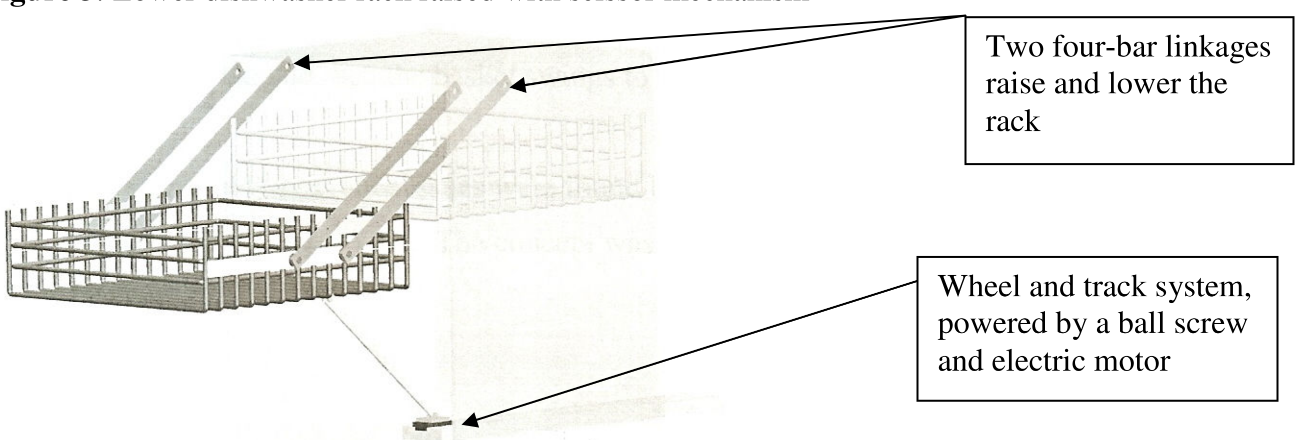


Figure 4: Lower dishwasher rack raised with a four-bar mechanism

Funding provided by National Science Grant No. 0234478, Principle Investigators: Lucy King and Tony Lin, Kettering University

Vertical and Horizontal Integration of Multidisciplinary Projects

Phase II is taking place in the 2007 winter semester with a variety of projects and prototypes will be built. The designs have been put into two categories, i.e., those being built by integrated and non-integrated project teams. The integrated teams include one or more students in EGR 409 (Machine Design II) and EGR 367 (Manufacturing Processes) or EGR 480 (Advanced Product Design) courses. Since there are 42 senior machine design students and only 11 senior product design and 12 junior manufacturing processes students, not every student could be placed on an integrated team. However, this situation allows for the opportunity to investigate whether the integrated teams will produce more innovative products with higher quality manufacturing than the non-integrated teams. The results might be difficult to analyze because many of the students have or are taking two or three of the courses involved in the integrated projects. Although it was not discussed with the students, students were hand-picked by the faculty for the integrated projects based on the quality of their work in previous projects. This is a common practice in the School of Engineering at GVSU. It complicates comparisons between groups, but the idea is to avoid situations were weaker students depend on stronger students to do most of the work.

Table 1 shows the organization of the integrated teams. Integrated projects involve students from more than one class. Some of the projects are already in the prototype stage, e.g., the Roast, Grind, and Brew prototype is shown in Figures 5. Table 2 lists the projects that are not integrated, i.e., the students in these teams are all in the same class.

Table 1 Vertical and horizontal integration of machine design, product design, and manufacturing project teams.

Project Description	Integrated Faculty	Number of Students		
		EGR 480 Product Design	EGR 409 Machine Design II	EGR 367 Manufacturing Processes
Roast, Grind, and Brew Project Second generation coffee machine prototype needed. Team must integrate control system from Electrical Engineering class and work done in EGR 380. Mechanism design, Heat transfer and packaging are all challenges for this team.	FARRIS (Lead) WALDRON	1	3	N/A
Winter Wrist Brace Project Previous work by Matt Anderson is proposing that the project continue with the construction of prototypes, and measurement against the current best practice.	FARRIS (Lead) WALDRON	2	2	N/A
Trap Thrower Automated trap thrower project sponsored by the Innovation committee at GVSU. Team must take initial prototype and refine into a product that can be sent to potential customers for review.	FARRIS (Lead) WALDRON	2	2	N/A
Pedal Pro prototype Bicycle torque measuring product project sponsored by GVSU's Innovation committee. Team must create a testable design from a paper design. Product enables the user to see the torque as a function of crank angle from each leg.	FARRIS (Lead) CHAPHALKAR	2	1	N/A
Prosthetic Hand Project Fluid powered prosthetic hand is under development by Elkins Innovation, a company housed in GVSU's smart zone. SOE helped company develop the foot control for the hand. Sponsor wants to develop actuators, pump, motors and valves suitable to application.	FARRIS (Lead) CHAPHALKAR	2	2	N/A
Dishwasher Rack Lift System Raises lower dishwasher rack to avoid muscle strain and injury.	WALDRON (Lead) CHOUDHURI	N/A	2	2

Funding provided by National Science Grant No. 0234478, Principle Investigators: Lucy King and Tony Lin, Kettering University

Chain-Drive Vacuum Improved durability for drive system to eliminate belt replacement	CHOUDHURI (Lead) CHAPHALKAR	N/A	2	2
Gear-Driven Wheel Chair Increased torque or speed wheel chairs	CHAPHALKAR (Lead) CHOUDHURI	N/A	2	2

Figure 5: Roast, Grind, and Brew integrated project

Organization of Non-integrated Projects

The non-integrated teams were selected by the instructors from the students that were not in an integrated team. Teams were created by the instructors, or in some cases students were allowed to self-select their teammates. Students were selected for non-integrated teams to build the dishwasher rack lift mechanism, chain-drive vacuum cleaner, and gear-driven wheel chair so that the experiences of the integrated and non-integrated teams can be compared. The rest of the machine design students who were not assigned to a team are working on the dishwasher mechanism, unless they developed their own design proposal. One example is a machine design team that is developing a sine plate to rotate a workpiece about multiple axes for machining operations. This project is sponsored by a local machine shop. Another team was created to help the school's SAE Baja team build a new gear case for this year's competition.

Table 2: Teams that are not integrated with other classes

Project Description	Faculty	Course
Baby Formula Mixer A new mother in the Entrepreneurship Program has suggested that there is a need for a product that will correctly mix water and powdered baby formula when the operator has been impaired by sleep deprivation. Team will be responsible for taking user need through to a product prototype.	FARRIS	**EGR 480** **Product Design**
Dishwasher Rack Lift System Raises lower dishwasher rack to avoid muscle strain and injury.	WALDRON	**EGR 409** **Machine Design II**

Funding provided by National Science Grant No. 0234478, Principle Investigators: Lucy King and Tony Lin, Kettering University

Chain-Drive Vacuum Improved durability for drive system to eliminate belt replacement	CHAPHALKAR	**EGR 409** **Machine Design II**
Gear-Driven Wheel Chair Increased torque or speed wheel chairs	CHAPHALKAR	**EGR 409** **Machine Design II**
Sine Plate Rotate a workpiece about multiple axes for machining operations	WALDRON	**EGR 409** **Machine Design II**
SAE Baja Gear Case Increased torque and protection for gears including heat effects	WALDRON CHAPHALKAR	**EGR 409** **Machine Design II**

Schedule and Logistical Considerations

Since some of the projects are already in the prototype stage, e.g., the Trap Thrower and the Roast, Grind, and Brew projects, while others are starting from scratch, it quickly became apparent that a significant amount of preparation was necessary to plan activities and monitor the progress of the integrated and non-integrated teams. Having teams from multiple classes should be a good experience for the students, but organization and scheduling strategies have to be developed.

The first task was to design and implement a master schedule for all the teams. The dates and deliverables are shown in Table 3 and include the mid-term design reviews, due dates for budgets and Gantt carts, deadlines for ordering materials, a Project Celebration event, and final sign-offs by the instructors. Initially the design reviews were going to be in each of the separate classes, but later a decision was made to have two afternoon meetings to review the teams' progress in mid-February. This allows more students, instructors, and guests to see the presentations, ask questions, and provide feedback.

Another consideration is the day-to-day communication between students and faculty, students within teams, and faculty to faculty. To facilitate increased communication, the web-based Blackboard system is being used to improve communication and share resources. The students are encouraged to use Blackboard's discussion board, e-mail, chat, and file sharing capabilities. In particular, using the discussion board will keep the discussion about specific topics all in one thread and avoid the challenge of finding related e-mails in student and faculty mailboxes. A separate blackboard site was developed for the projects. This allows the formation of teams in the site across class boundaries.

Table 3: Common milestone dates for the integrated and non-integrated projects

Monday, January 8, 2007: Start of winter semester
Tuesday and Wednesday, February 13 and 14 (2:00 – 6:00 PM): Design reviews
Friday, February 23: Initial budgets and Gantt charts due
Saturday, February 24: Faculty meeting for approval/correction of budgets/timelines
March 4-11: Spring Break **=> order materials before March 1**
Thursday, April 19: Project Celebration
Friday, April 20: Project sign-off
Saturday, April 21: End of winter semester

Funding provided by National Science Grant No. 0234478, Principle Investigators: Lucy King and Tony Lin, Kettering University

Progress at Mid-Semester

Preparations began last summer and included faculty attending a seminar at Kettering University. Many meetings have been held to develop the common projects, integration structure, methods for monitoring the integrated and non-integrated groups, and plans to provide outsourcing and assessment. Design reviews were held in mid-February (just over a month into the semester) for the integrated and non-integrated teams. The early design reviews does not allow the teams to procrastinate and allows the teams to have time to act upon the feedback they receive at the review. Each team gave a presentation that included brainstorming, concept generation, plans of attack, timelines, and budgets. The design reviews were attended by all the instructors and other faculty in the School of Engineering. Kettering University faculty were also invited. Written evaluations of the presentations were provided by the faculty, and every student was required to attend and submit evaluations of two presentations. The students also had to submit peer reviews and evaluations of their own performance. These evaluations were used to identify teams that were functioning poorly so that appropriate action could be taken early before the end of the semester.

Some of the teams' design ideas and approaches had merit and exhibited a solid background in engineering fundamentals. Unfortunately many teams suffered from similar problems. From a curriculum point of view the most disturbing problem involved the students' lack of ability to use their theoretical analysis of a problem as a basis for their design decisions. In fact some teams treated their design and analysis efforts as two separate and unrelated activities. More than once free body diagrams, static and dynamic analyses, and math modeling efforts were ignored when designs were conceived and evaluated. The authors have identified two strategies to remedy this problem. First the assignments leading up to the first design review can be revised to stress the linkage between analysis and design. The second strategy is more difficult to implement. The students need to have more opportunities to practice applying their analysis skills to open ended design problems. In the School of Engineering at GVSU, design projects are already a part of many sophomore and junior level courses. Many of the teams' presentations make a convincing case that these projects should be reviewed for their content and effectiveness.

Generating and analyzing alternative solutions to a given design problem was another common problem. Although the teams were required to generate three alternative solutions, many teams had generated one serious alternative and two obviously inferior variants of the first design. Worse yet, the selection of one alternative was not based on engineering principles. In the future the faculty will require that each team generate three alternatives designs based on different working principles. The teams will have to prove the viability of each design through a rigorous analysis. To enable this change the projects must be presented in terms of the needs of the customer and not in terms of the desired technology. All descriptions of projects should be solution neutral. For instance the "chain-drive vacuum" project should be presented as a project to improved the durability of vacuum drive systems and eliminate the need for users to perform maintenance such as belt replacement. A similar change would need to be made in the description of the "gear driven wheel chair" project. Of course more open-ended projects will mean that faculty may lose control of what the technology the solution will incorporate. This

Funding provided by National Science Grant No. 0234478, Principle Investigators: Lucy King and Tony Lin, Kettering University

can be a problem if the professor of a class insists that a certain technology be incorporated into the solution in order to reinforce the material presented in the class.

As discussed above, some teams did not have viable designs. One concept for a gear-driven wheel chair is shown in Figure 6, but turning the hand crank would be an awkward motion. The teams had a difficult time choosing a design that would make it easier for people in wheel chairs to go up handicap ramps using gears without electrical power. The use of electrical power was prohibited by the project statement. One faculty member suggested that electrical power might be necessary to satisfy customer needs. He encouraged an "out-of-the box" approach that involved requesting that the non-electrical constraint be removed.

There were also problems with the chain-driven vacuum cleaner projects. The goal was to reduce customer maintenance by retrofitting a belt-drive vacuum with a chain-drive system. The problem was that chain manufactures do not make a chain small enough to work with the high-speed motors in vacuum cleaners. The integrated team decided to change to a direct-drive from the motor to the vacuum brush with a shut-off switch if the vacuum jams. Finding a location for the electric motor was a problem so the students are trying to put the motor inside the roller-brush assembly (See Figure 7).

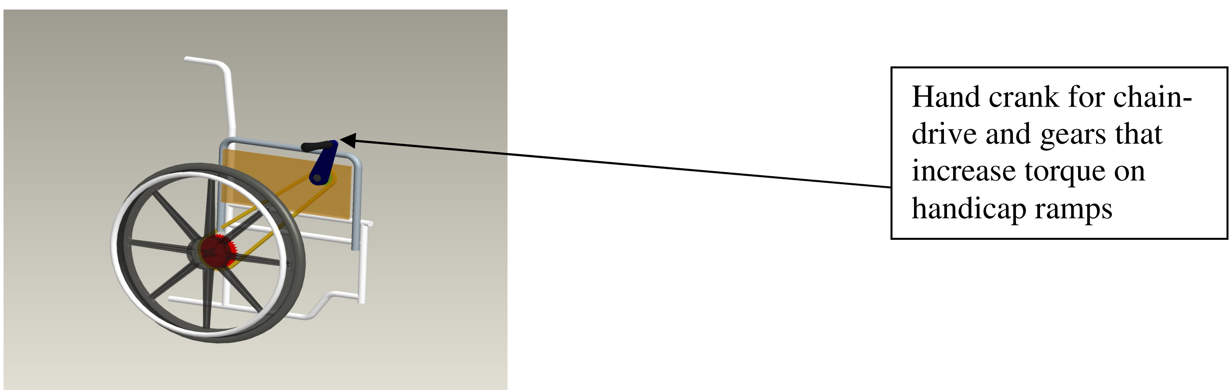
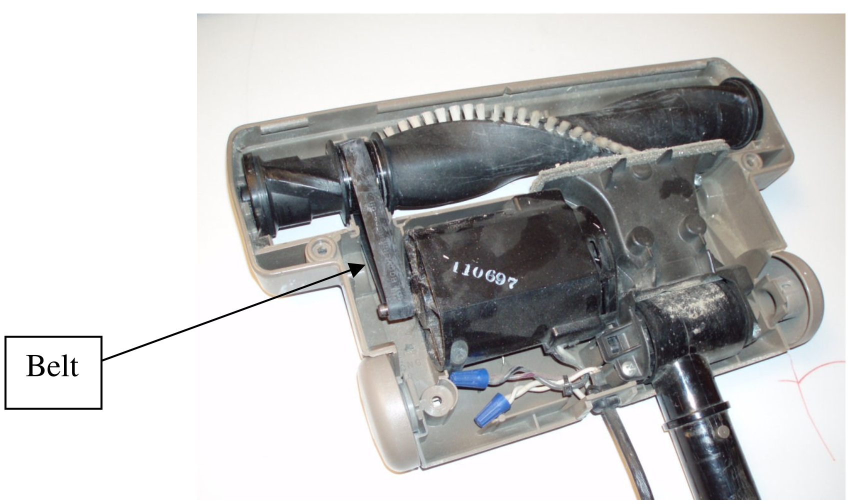


Figure 6: Concept for gear-driven wheel chair integrated project



Funding provided by National Science Grant No. 0234478, Principle Investigators: Lucy King and Tony Lin, Kettering University

Figure 7: View of standard vacuum cleaner with belt

Funding provided by National Science Grant No. 0234478, Principle Investigators: Lucy King and Tony Lin, Kettering University

Another interesting situation involved the integrated and non-integrated dishwasher teams. The integrated team designed a system that included springs to assist the raising of the lower rack. The four-bar mechanism and gears are shown in Figure 8. The problem is that many people with injuries or handicaps cannot bend down to reach the lower rack. Furthermore, after filling the lower rack, the design required the user to push the lower rack down into the dishwasher enclosure (aided by the weight of the loaded rack). This design might be helpful for people with minor disabilities, but it would not be acceptable for the targeted customers.

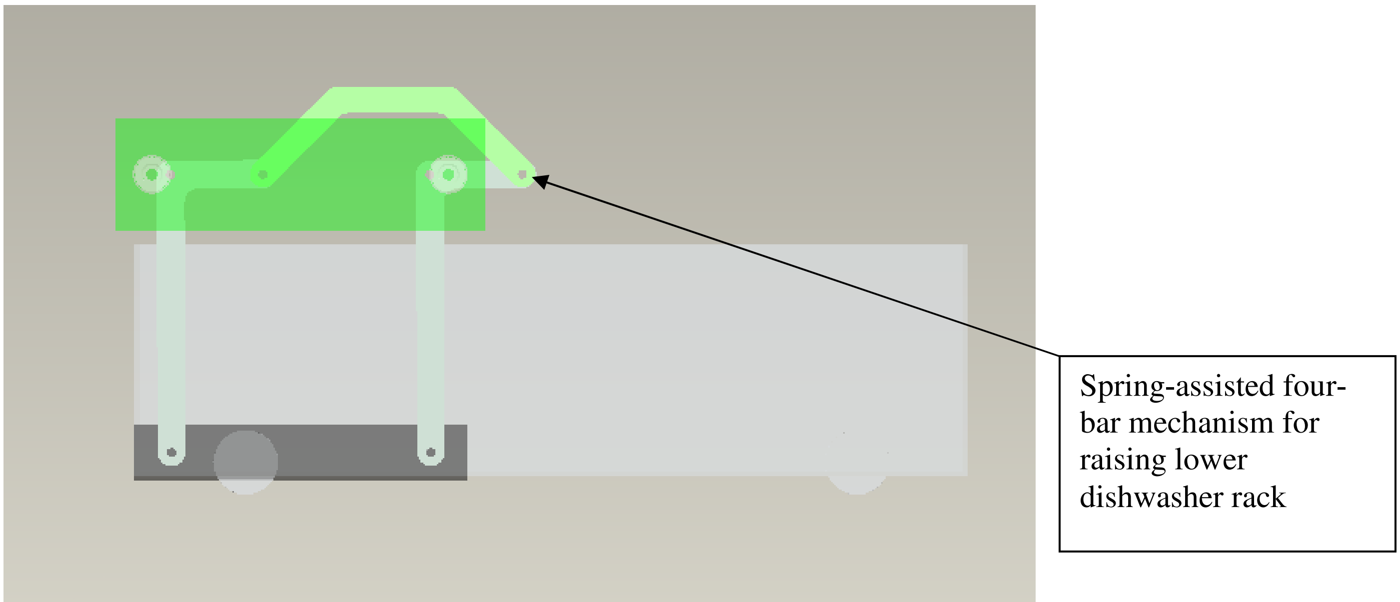


Figure 8: Integrated team concept for raising lower dishwasher rack

The non-integrated team developed a design that was based on the idea that it would best if an “add-on” could be easily attached to the existing racks. A simple design was proposed with four brackets that rigidly attach the upper rack to the lower rack. The upper rack would be replaced with a deeper rack, similar to lower rack. The idea was that it might be sufficient to have access to one “deep” upper rack that could be rolled out along with the existing lower rack. Investigations are necessary to see if one deeper upper rack is acceptable for a sufficient percentage of the target market, but the addition of brackets to support the upper rack is certainly a very convenient and cost effective design.

Assessment

In order to fully benefit from this effort, assessment must be developed, data must be reviewed, and changes must be considered and implemented to improve the experience for students and faculty. For this reason, a faculty member in the School of Education was asked to provide some suggestions. Two lists are shown in Tables 4 and 5 of questions related to student issues and issues for faculty and outside evaluators. These questions will be presented in surveys at the end of the semester, and the responses along with the faculty and student evaluations will be used to help understand the students’ positive and negative experiences in this project.

Funding provided by National Science Grant No. 0234478, Principle Investigators: Lucy King and Tony Lin, Kettering University

Table 4: Student Issues

A. Team Work – Are the student teams functioning well?
a. How well did the members of your team cooperate?
b. How much conflict did you experience within the team?
c. How much did you learn from the members of your team?
d. How evenly was the work distributed within your team?
e. How well did your team plan ahead?
f. How creative was your team?
g. Would you have preferred to conduct the course project individually rather than in teams? Why? Why not?
h. Do you think a team project or an individual project would be more beneficial in developing your knowledge and skills? Why? Why not?
i. Do you have some suggestions for us on what we might do differently with future team assignments to better develop your knowledge and skills?
B. Individual Work – What knowledge and skills did the students use on the project?
a. How much creativity did you use to solve the design problem?
b. How much did you rely on knowledge and skills gained in your classes this semester to solve design problems?
c. How much did you rely on knowledge and skills not covered in classes to solve design problems?
d. How satisfied were you with your project experience?
e. How difficult was your design problem?
f. What grade do you think your project deserves?
g. How much did the project increase your ability to tackle poorly defined problems?
h. How much did the project increase your ability to learn new knowledge and skills on your own?
C. Design Process followed
a. How well did your team follow a design process?
b. Did your team make design trade-offs during the design process?
c. How seriously did your team consider alternative designs?
d. How well did your team use technical models to refine your design?
D. Project Success -
a. How well did your prototype meet the design specifications?
b. How innovative is your solution to the design problem?
c. How well was your prototype built?
E. Demographic Data – Data that will allow us to make comparisons between groups.
a. Was your project sponsored by an outside group of company?
b. What EGR classes are you taking this semester?
c. What is you Major?

Funding provided by National Science Grant No. 0234478, Principle Investigators: Lucy King and Tony Lin, Kettering University

Table 5: Issues for faculty and outside evaluators

A. Assessment of the Prototype
a. Build Quality (perhaps a rubric)
b. Performance versus the specifications.
B. Assessment of intermediate work products.
a. Specifications and constraints
i. Complete?
ii. Reflect the desires of the sponsors?
b. Quality of alternative concepts generated
i. Are the alternative concepts documented well?
ii. Are they based on different operating principles?
iii. Do they meet the design constraints?
c. Concept selection process
i. Based on technical models?

Conclusion

This paper is a summary of ongoing efforts to improve the experiences of students in project teams and to help machine design, product design, and manufacturing students make the transition from designing components to designing and fabricating mechanical systems. Some results and observations have been presented. One challenge has been to balance the goals of developing designs that involve technical considerations that are covered in the associated courses and developing designs that are marketable on a cost and need basis. Future papers will be offered that discuss the remaining portion of the project as well as the activities and approaches that help students benefit from working in project teams.

References

1. J. Oliva and W.K. Waldron Jr., "Virtual Design Competitions in a Computer Aided Engineering Course," *Proceedings of 2004 ASEE/NCS Conference*, Western Michigan University, Kalamazoo, Michigan (2004).
2. R. Echempati and W.K. Waldron Jr., "Concurrent Product and Process Development for Metal Forming Operations," *Proceedings of TMCE 2004 Symposium*, Lausanne, Switzerland (2004).
3. W.K. Waldron Jr. et al., "Learning Module for using Dynaform to Study the Effects of Die-Entry and Punch-Nose Radii on Drawing Cups," *Proceedings of 8th International LS-DYNA Users' Conference*, Dearborn, Michigan (2004).
4. C.J. Hoff, W.K. Waldron Jr., and P. Zang, "Early Introduction of CAE Tools Enhances Success in Student Design Competitions, "*Proceedings of ASEE/IEEE Frontiers on Education Conference*, Savannah, Georgia (2004).

Funding provided by National Science Grant No. 0234478, Principle Investigators: Lucy King and Tony Lin, Kettering University