From Structures to Automation in Freshman Civil Engineering Projects

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Abstract: For the last four years, we have offered a cornerstone design course to first year students of civil engineering at National Taiwan University. This mandatory course is centered on design-build-test projects, blending digital design with physical model fabrication and testing. For the first two editions of the course, the project scope was limited to structures, and centered on scale models of roof structures made of jet-cut aluminum. These last two years, we have supplemented structural aspects with a transportation automation component, including system design, motor control, and Arduino board programming. In this contribution, we describe this new version of the course, and extract some lessons on how to enrich students' learning experience. Strategies we have found useful include self-paced tutorials and peer review, theory-based design aids, and an enlivened load testing process.

Keywords: Freshman Design, Project-Based Learning, Structural Engineering, Transportation Engineering.

Introduction

These last four years, our Department of Civil Engineering has been engaged in a sustained effort to enrich the undergraduate curriculum with stronger design and practice-oriented components. Building on pilot tests (Ni *et al.*, 2011), we now offer a sequence of project-based courses called cornerstone, keystone, and capstone courses, directed respectively at first, second, and third or fourth year undergraduates (Capart *et al.*, 2013). The sequence works well overall, with each course allowing students to acquire skills that they can build upon in later courses. Within this sequence, the cornerstone design project offered the second semester of the first year is especially important. As a mandatory core course, it aims to provide a foundation in terms of design skills, and motivate interested students to pursue design and practice-oriented projects in subsequent optional courses. At other schools, related approaches to civil engineering design education have been described by Arciszewski (2009), Thompson (2010), and Einstein (2013).

Our department therefore allocates to this course an unusual level of resources. Instead of the three sections adopted for most courses, the course splits our class of 120 students into six separate sections, with each section addressing a smaller group of 20 students. The course is taught by a team of six instructors, aided by teaching assistants, student teaching assistants, and technical staff. Support from our alumni and the Ministry of Education also allows us to support the course with the requisite materials and equipment, including a computer-controlled water jet cutting machine, used to transform students' digital designs into functional parts. To make the most of these resources, we have devoted considerable efforts to designing course contents and approaches that seek to maximize student learning and achievement. For the first two editions of the course, the project scope focused on structures, and culminated in the construction of scale models of roof structures made of jet-cut aluminum and poured gypsum. These last two years, we have sought to further improve and enrich the course, by refining the structural design-build-test component, and by including a new transportation automation component. One key goal of the course is to let students learn how to navigate between the digital and physical world, from digital design to the construction of structural and mechanical prototypes and back to digital control.

To tie in with the cornerstone project, two mandatory courses which used to be offered in the third year of the curriculum have been moved up to the first year. The first is engineering graphics, now taught in the first semester of the first year, which equips students with the basic skills needed for digital design. The second is computer programming, now taught in the second semester in parallel with the project, which equips students with the logical design and computer coding skills needed for the design and programming of automated systems. As the project now includes both static and dynamic components, it also ties in more fully with the engineering mechanics course, also taught in the first year.

In this contribution, we describe the structure-to-automation projects proposed these last two years. Although both projects combined structures and automation, the two design briefs differed a great deal, and we discuss the corresponding advantages and drawbacks. We also describe strategies adopted for both projects that we found particularly useful, including self-paced tutorials and peer review, theory-based design aids, and an enlivened load testing process.

Project Briefs

Space Structures Linked by a Conveying System

The project brief for the Spring 2013 edition of the course was our first attempt to integrate structural issues with an automated transportation component (figure 1). For the first part of the semester, pairs of students were tasked with designing, building and testing a functional scale model of a large span roof structure. Mounted on a wood base of size A1, the roofs were to span a footing-free area of size A2. Students were to build their structures from aluminum components of their own design, cut from a single plate of size A3 and thickness 4 mm, complemented by bolts and steel cables.

The load-bearing requirement was the ability to support metal blocks weighing 2.5 kg each, at least 105 mm above ground, and distributed over as wide an area as possible for a total of minimum 50 kg and maximum 100 kg. In addition to this functional requirement, the brief challenged students to design elegant and expressive structures.

For the second part of the semester, aggregated teams of four students were tasked with designing, building and testing an automated conveying system linking their two space structures. The payload to be delivered back and forth was a single steel sphere, using a system composed of a programmable Arduino board (Motoduino), electrical motors and switches, jet-cut aluminum components, steel cables and aluminum rods that could be used as rails for spheres to roll on.

Figure 1. Spring 2013 cornersone project: space structures linked by a conveying system, fabricated from jet-cut aluminum and steel cables. Top: completed structure and load-testing. Bottom: automated system shuttling spheres back and forth.

Earthquake-Resistant Automated Parking Tower

For the Spring 2014 edition of the course, a new project brief was developed, challenging students to design, build and test an earthquake-resistant automated parking tower (figure 2). Students worked in stable teams of three throughout the semester. In the first part of the semester, students designed and constructed a three-story earthquake-resistant tower.

To be mounted on an A3 wood plate, the structures were to be assembled from student-designed aluminum components, jet-cut from an A2 plate of thickness 4 mm, complemented by three viscous piston dampers. Although viscous dampers of identical specifications were provided to all groups, students were free to choose damper positions and configurations which they thought would give the best energy dissipation properties.

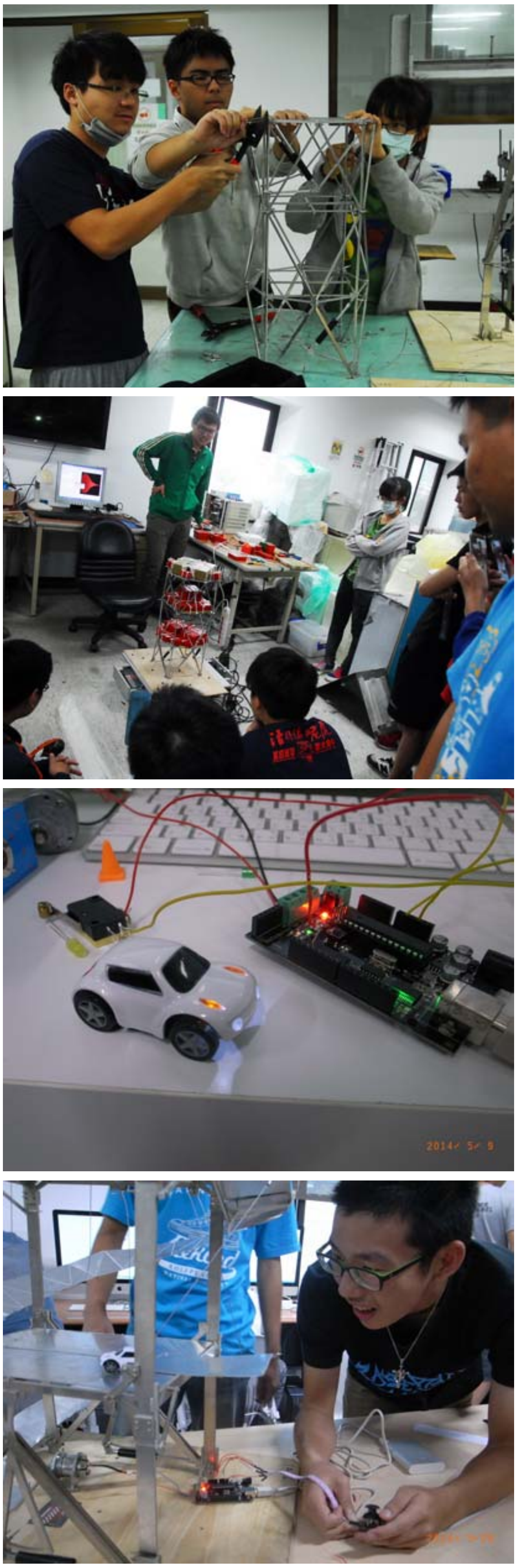

Figure 2. Spring 2014 cornersone project: earthquake-resistant automated parking tower. Top: tower assembly and load testing using a shaking table. Bottom: Arduino-controlled model cars and their test drive up and down the tower.

The structural load-bearing requirement was to support steel blocks on three floors, and resist earthquake loads of up to 0.5 g peak ground acceleration generated by a shaking table.

For the second part of the semester, students were to equip their tower with a car access ramp, allowing the up and down circulation of remote-controlled model cars (ZenWheels R/C Microcar). Although these cars were originally designed for control by an iPhone, students were tasked with wiring and programming an alternative control system composed of an Arduino board, blue tooth connection, and joystick. In addition to these functional requirements, students were again challenged to design expressive and attractive towers

Advantages and Drawbacks of the Two Briefs

Although the two structural briefs focused on different types of structures (large span roof versus multi-story tower), they have a number of common advantages. First, they allow repeating elements (parallel beams or stacked floors) yet provide a large range of possible variations in structural configurations and assembly details. The prescribed dimensions (spans, heights, size and thickness of aluminum plates from which components were cut) were carefully chosen to require relatively slender structures for which differences in design would lead to large differences in behavior.

Load testing produced a variety of failure modes, including overall instability, large deformations, bending failure, element buckling, and connection failures. The large span roofs required students to carefully consider how to combine aluminum members and steel cables (for elegant examples, see Saitoh and Okada, 1999). The earthquake-resistant tower required students to think about how their structure would respond to dynamic loading, and how best to use viscous dampers to damp shaking-induced oscillations (for background, see Hwang et al., 2005). The opportunity for students to find out how structures of their own design respond to static or dynamic loads is certainly one of the highlights of the course.

For the automation component of the course, the two briefs feature more contrasted advantages and drawbacks. Building an automated sphere conveyer system required students to devote much time and effort to mechanism design and tinkering. To help students, we provided a tutorial example consisting of an elevator device, and many groups chose to include this as a component of their design with only minor variations. Other groups, however, chose to explore very different types of mechanisms including swings, cable cars, a staggered staircase, a catapult, and rotary conveyers.

It turned out that mechanism design and implementation had a much greater influence on success than the computer coding aspects of system control. Although some Arduino controlled systems did well, the best system by far was a student-designed rotary belt conveyer which required no programming at all, with the motor operated continuously to handle a payload of multiple spheres. Adventurous students, therefore, learned more about mechanisms and mechanical systems than about computer programming, which had been our original target. Other drawbacks were a low need for integration between the space structure and transportation components of the project, and a lack of realism of the brief. Who needs to send spheres back and forth between space structures anyways?

For the automated parking tower, the use of a model car as basic transportation vehicle had a number of advantages. First, it reduces greatly the mechanical complexity of the project, and allowed students to devote more effort to the wiring and coding aspects of car control. Integration of the vehicle ramp with the structural tower also required students to produce more integrated designs. Finally, the project benefited from a much greater degree of realism. Civil engineers do wish to design earthquake-resistant structures through which cars can smoothly circulate.

On the downside, the range of possible variations for car ramp designs is more limited than for sphere-conveying mechanisms, providing fewer opportunities for creative invention. Moreover, it again turned out that good ramp geometry (with a grade not too steep and few sharp turns) has a greater influence on successful car circulation than the coding of the car remote control system. We have thus not yet found the brief which will truly reward student efforts to design good software as well as good hardware. In a future edition, one option we may pursue is to require software control of the cars, without human intervention. The project could thus involve designing a piece of infrastructure for self-driving cars.

Useful Strategies for Student Projects

Self-Paced Tutorials and Design Review Sessions

In project-based courses, most learning occurs as students actively engage in design, construction and testing. The time devoted to exposition and instruction should therefore be limited to a minimum. Nevertheless, students need to master many skills and absorb a great deal of information to produce digital designs that can be successfully fabricated from their digital files, and to write code that successfully interfaces with electrical and electronic components. Instead of standard classroom instruction, we provide the requisite material to the students in the form of step-by-step tutorials, posted online (figure 3). In class or at home, students can go through these tutorials at their own pace, and use them as reference as they go about their design work. Instructors and teaching assistants can then focus their time on helping students address the specific difficulties they encounter, without holding up or interrupting everyone’s work. Compared to a typical course preparation, the investment required to prepare these tutorials is considerable, but it is repaid many times over. Prepared to a high quality standard and made available to each of the six sections, they allow 120 students to work asynchronously and autonomously.

In addition to letting students work in teams on their projects, time freed up in this way can also be used for design reviews (figure 4). These are formal and informal sessions during which students discuss their evolving designs with instructors and peers. When given the opportunity and encouraged to do so, we have found that students can provide helpful suggestions and constructive criticism to their peers. For instructors, informal discussions with students as they work provide great opportunities to get to know students better and provide tailored feedback and encouragement.

Figure 3. Self-paced tutorial allowing students to learn how to wire Arduino boards.

Figure 4. Design review session during which students present their evolving design and obtain feedback from instructors and peers.

Theory-Based Design Aids

The project briefs and model-making technology adopted for the course encourage students to integrate cables or dampers into their designs (figures 5 and 6). To help students identify good ways of using these elements, short theory-based lessons were scheduled in the first weeks of the semester. The emphasis is on operational knowledge that students can apply to their own design. For the Spring 2013 roof project, we taught students to analyze constant chord force trusses using form and force diagrams (Allen and Zalewski, 2010; Lachauer and Kotnik, 2010).

For the Spring 2014 tower project, we taught students how to estimate damper amplification factors for different toggle brace configurations using small deformation analysis (Costantinou *et al.*, 2001; Hwang *et al.*, 2005).

Both types of analysis can be performed graphically using pencil, ruler and protractor, and can be applied to a great variety of geometrical configurations. They can be learned by first year civil engineering students in a matter of hours via teacher instruction, in-class exercises and homework.

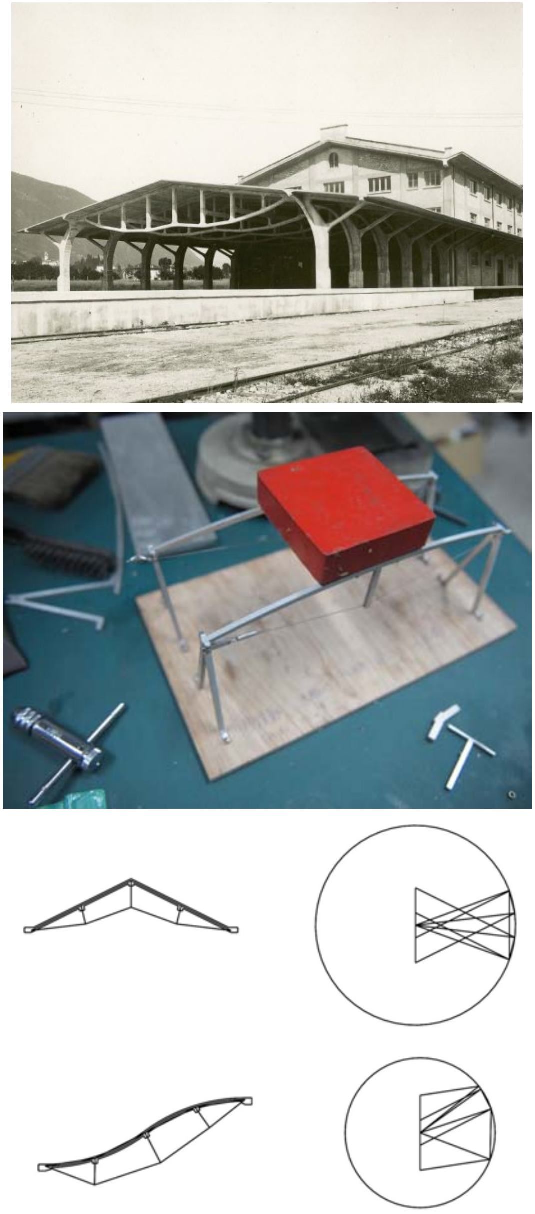

Figure 5. Constant chord force trusses and their graphic statics analysis. Top: Robert Maillart's Chiasso Shed (Source: ETH Bildarchiv). Middle: a demonstration structure using jet-cut aluminum and steel cable. Bottom: form and force diagram analysis.

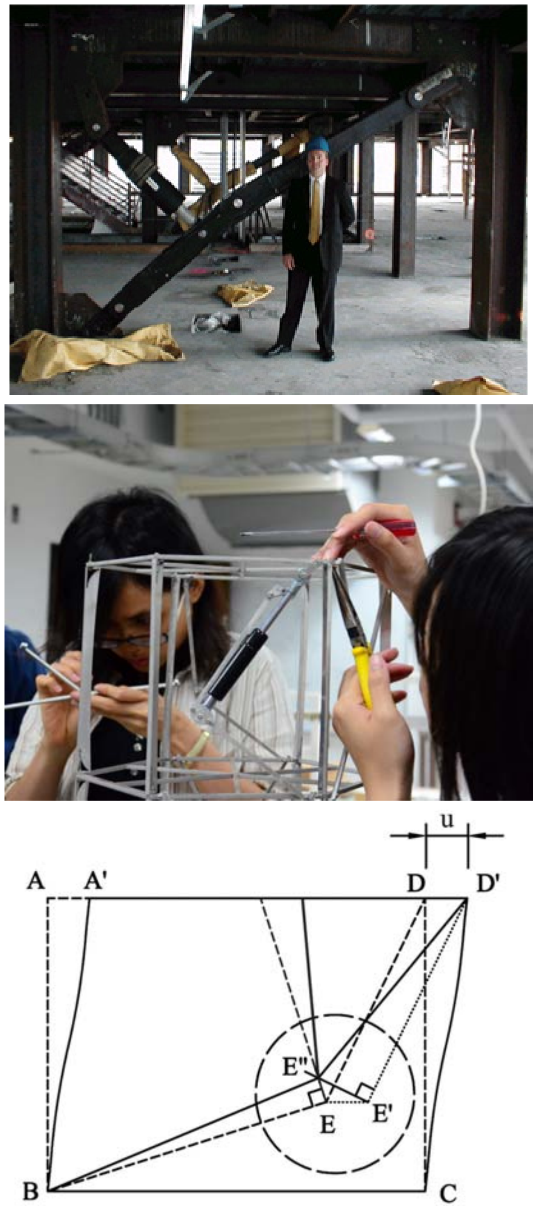

Figure 6. Toggle brace configuration improving the performance of viscous dampers. Top: real example at the Yerba Buena Tower (Source: Teratec). Middle: students integrate a toggle brace into their tower structure. Bottom: graphical analysis.

After practicing on structural configurations supplied by instructors, students can analyze new configurations of their own design. Requiring only a few hours of semester time, these design aids provide an early opportunity for students to connect theoretical analysis and practical design.

Decision-Based Load Testing

One of the highlights of the course is the load testing session, during which students subject their scale models to static or seismic loads. In the first two years of the course, we adopted a one-dimensional load testing procedure, in which a rod suspended from a single point at the centre of the structure was gradually loaded with heavier and heavier weights. The score was then calculated from the maximum load before failure or, for structures that did not fail, from the deformation monitored at the loading point. Although it does allow assessment of structural behavior, the loading process conducted in this way is rather mechanical and reduces the students to passive observers (save for adding weights and taking deformation measurements).

For the last two years, we have used a different approach: a decision-based loading process during which students decide at each step where and how much they want to continue adding loads to their structure. For the roof project (figure 7), this was done by letting students add standard weights (2.3 kg steel blocks) anywhere over the surface of their roofs. To encourage well-distributed loads, a score of 1 point per block is given to the first layer of blocks, a reduced score of 1/2 point per block for each block piled over another to form a second layer of blocks, a score of 1/4 for the third layer, etc. For the tower project (figures 8 and 9), students added weights to the floor of their choice (second, third, or fourth floor), scored respectively by a weighting factor of 1, 2 or 3, and decided on the level of ground acceleration they wanted to subject their tower to, with the total score calculated as the product of factored mass by peak ground acceleration.

The decision-based load testing process has turned out to be much more engaging than the former procedure. During testing, students are intensely concentrated on identifying optimal ways of loading their structure, maximizing their performance score before the structure fails. As different students have different appetites for risk, students of the same group must also negotiate among themselves to decide how far they wish to push the tests. Many groups tested their structure to total failure, either because they overestimated its capacity, or because they were curious to see how far it would go and how it would fail. Students from other groups also enjoy witnessing the process, usually encouraging greater risk taking.

Figure 7. Load testing of the roof structures, Spring 2013. Top: students decide to add one more steel block, leading to collapse. Bottom: students argue whether to continue adding weights. They stopped before the structure suffered more than local damage.

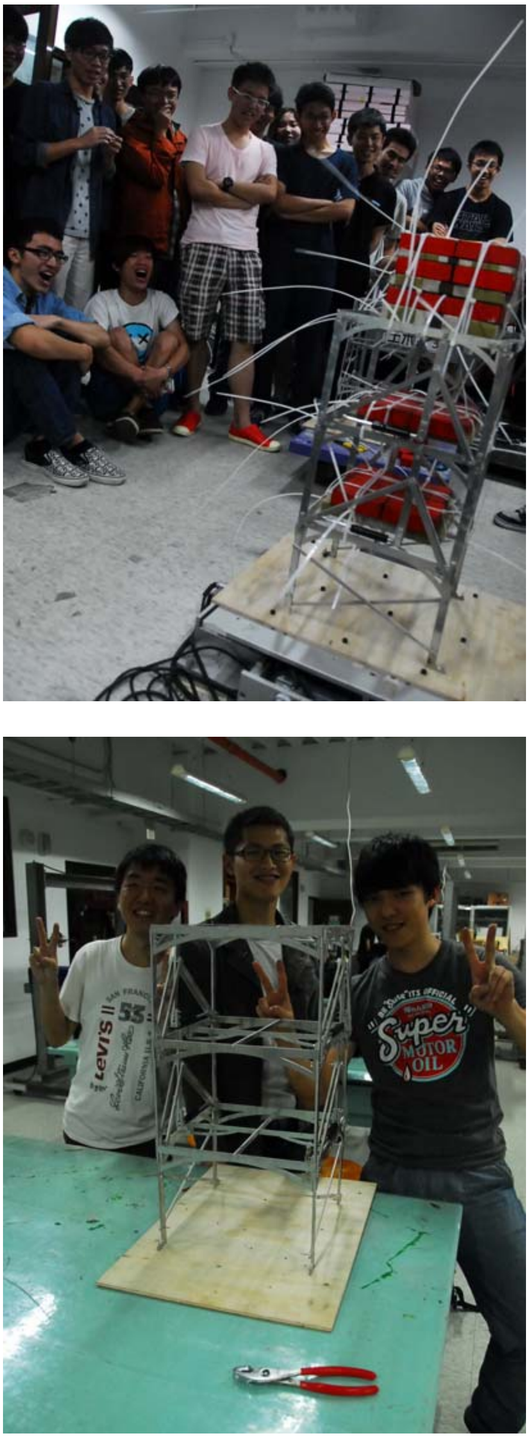

Figure 8. Decision-based load testing of the tower structures, Spring 2014. These students decided to heavily load the top floor of their structure… yet it survived seismic shaking.

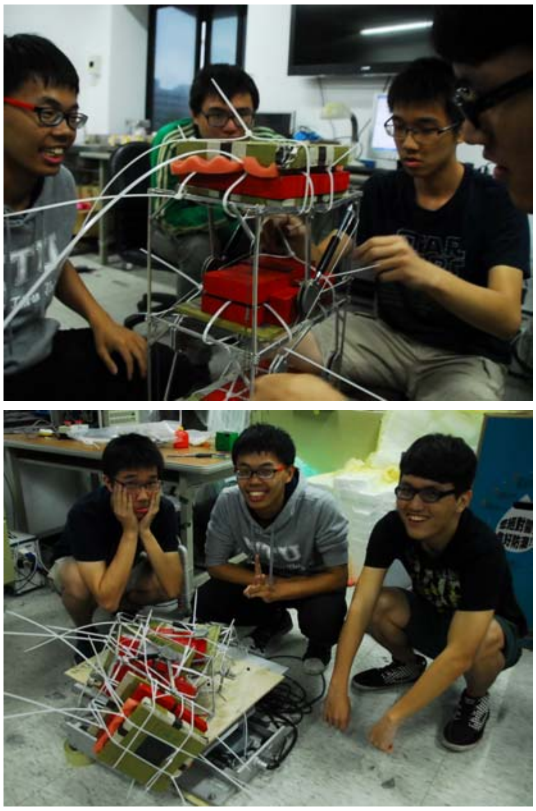

Figure 9. Decision-based load testing of the tower structures, Spring 2014. These students were more conservative, but earthquake shaking caused their tower to suffer complete collapse.

Conclusions

Results from student evaluations for the Spring 2014 semester are not yet available, making it difficult to compare how students have experienced the two structure-to-automation projects conducted so far. Nevertheless, the Spring 2013 edition of the course, combining structures with automation, generated substantially higher levels of student satisfaction than the previous editions focused on structures alone. As another indication of heightened interest, students who experienced that edition of the course were more likely to enroll in the optional keystone design project course offered in the second year. Whereas in previous years, about 25 students signed up for this very time intensive follow-up course (described in Capart *et al*., 2013), this year 50 students signed up (unfortunately, enrollment had to be capped at 35). Compared with previous classes, moreover, this crop of students showed greater fluency with system and mechanism design. Although further efforts will be needed to improve the automation component of the course and its integration with structural aspects, combining these two components is proving to be a fruitful way to enrich our cornerstone design course.

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