Rethinking the Machines in Which We Live

A Multidisciplinary Course in Architectural Robotics

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Attempting to bridge the educational gap between robotics and other disciplines is always challenging, but it is likely to provide interesting results. This point is exemplified in a graduate-level class, architectural robotics, enrolling students from electrical, computer, and mechanical engineering as well as human factors psychology and architecture [1]. Architectural robotics is formally defined in [2] as “intelligent and adaptable built environments (featuring embedded robotic components) that sense, plan, and act.” In [2], which sets out a vision for architectural robotics, Gross and Green assert that “perhaps the greatest challenge for architectural robotics is defining the community” and ask, “who is cultivating this line of research?” We believe robotics professionals should play a major role in defining and leading this emerging field. The class discussed in this article is aimed at defining the scope of the field and its community from a robotics perspective.

The class is cross-listed in the Electrical and Computer Engineering and Architecture Departments at Clemson University and engages multidisciplinary teams of students in open-ended hardware-based projects focusing on robotic systems working in, or augmenting, the built environment. While the classical education in these disciplines highlights the design as a key element, what design means and how students are exposed to it differ significantly between each population.

The motivation of the class is to promote collaborative research between the two title fields; this is a promising area but has so far been elusive in providing concrete benefits to society. While extensive progress has been made within robotics subdisciplines over the past several decades, its transition into technologies affecting the world in which we live has been relatively slow. Despite promising robotics efforts in health care, surgery, rehabilitation, domestic environments, and education [3, Ch. 52–55], robots are still largely restricted to industrial, remote, and hazardous environments [3, Ch. 42 and 47]. Robotics still awaits that singularity that will, as predicted in innumerable science fiction stories, make robot use widespread and ubiquitous in people’s everyday existence.

One engineered product familiar to all and often overlooked by technologists is the built environment inhabited by humans at wide-ranging scales, from that of furniture to that of the metropolis. In shaping the built environment, architects collaborate with engineering disciplines outside of robotics (e.g., structural and civil engineers) to bring the added value of form making (aesthetics), framing of human activity (programming), and technical performance/expression (tectonics). The tectonic aspect of the built environment has long been advanced by architects and consulting engineers and has intensified in recent years with the advent of increasingly advanced technologies and methods, particularly as a result of the information technology revolution. Curiously, despite this advancement, there has been almost no incursion of robotics or its elements into architecture or built environments. Architecture as a field has a long and rich history of innovation [4], and its economic impact vastly overshadows that of robotics. Widespread adoption of robotic technologies within architecture would likely have a major positive impact on robotics.

Robotics Interfacing with Architecture

Two highly desirable activities arise naturally from the abovementioned discussion: 1) identification of ways in which robotics, in its current state, can transition usefully into architecture and 2) identification and removal of the key barriers currently preventing such transitions.

Digital Object Identifier 10.1109/MRA.2013.2287456

Date of publication: 24 June 2014

1070-9932/14©2014IEEE

We believe the key barriers to progress in 2) are interdisciplinary communication and, more importantly, the lack of corresponding education at the graduate level. The architectural robotics course is thus aimed, at the high level, to be at the intersection of architecture and engineering and, at the detailed level, to develop common concepts necessary for creating new robotic environments.

Visions and early investigations on robotics interfacing with architecture have begun to emerge. Mitchell [5] postulated that in the near future, "our buildings will become... robots for living in." Subsequent efforts have concentrated on either adding sensory/computational elements to existing architecture (smart buildings) [6], [7] or introducing self-contained robots into existing spaces [3, Ch. 55]. The second approach appears to be the obvious way to introduce robotics into architecture. However, it is argued here that a more interesting (and practical) approach involves a tighter coupling of the fields, applying robotics techniques and theory to move the mass that forms the core shape of the environment.

The explicit goals of this graduate-level course at Clemson University are to explore the boundary between robotics and architecture and promote creativity at their intersection while addressing the challenge of widely differing expectations between the engineers, architects, and psychologists. All of the course activities are designed to be open ended, with the key objects being the creative process and design methodology rather than any specific end product. This has led to valuable insight into the nature of inherent disciplinary biases and the surprises that can result when the creative strengths of the two fields are suitably catalyzed.

This course is not the first effort aimed at combining engineering and other disciplines in graduate classes [8]. However, it is unique in that it focuses on the robotic elements as an integral part of environmental design (e.g., in plumbing, air conditioning, etc.) as opposed to being introduced into a previously built space. The first offering of the class in the spring 2009 semester was found to be the richest in terms of new pedagogical information and is thus the focus of this article. The extensive feedback and suggestions (mostly oral) provided by the students factored greatly into the design and structure of the class in subsequent semesters.

Course Structure, Hardware Technologies, and Components

The underlying philosophy for the class is to allow students from each discipline to experience the creative efforts and methodology of the other discipline(s) firsthand while simultaneously using their own disciplinary expertise. We believe that joint exploration of a project using hardware (at a reduced scale given the nature and cost of most architectural applications) is the most effective approach. Since this philosophy entails an intensive collaboration of architects and engineers, a commonly usable hardware basis for the class projects was required.

An inexpensive and readily available platform, Arduino [9], had previously been used by both architects and engineers [10]; hence, its selection was a natural choice. A varied suite of sensors, actuators, and construction material was made available, including stepper and servomotors, light-emitting diodes (LEDs), infrared and optical sensors, and limit switches, as well as LEGO products, Bosch framing components, card paper, etc., some of which are shown in Figure 1. The purchase of more specialized components was sanctioned depending on the requirements of the project and their potential for long-term use in the class.

Visualization software and rapid prototyping tools were also extensively used. The architects made virtual 3-D models using Rhino and AutoCAD and physical models using CNC laser cutters and milling machines. This process expedited critical analyses, allowing for quicker identification and mitigation of various challenges posed during the design and development stages. The students did not have external support in the form of departmental engineers or technicians, although there was no ban on seeking help. However, most of the students had experience with machining tools, and they were encourage to assist one another.

The size of the class was kept small due to the limited availability of laboratory space, machining equipment, and components, and thus no project management tools were required. However, such tools could be used if the scope, time frame, and complexity of the projects were altered. The class was designed to be an active learning experience, partly due to the hands-on approach required from the students toward project design and delivery as well as an experiment in the studio technique used extensively in architecture, similar to [11].

The primary method of assessment was a set of three multiweek projects. Students were paired together in two-person engineer–architect teams (also engineer–psychologist teams in subsequent iterations); the combination was changed for each project to maximize the diversity of interaction and expose each student to varying thought processes. This was essential given the varying student experience levels; registrants ranged from first-year graduate students (one engineering and

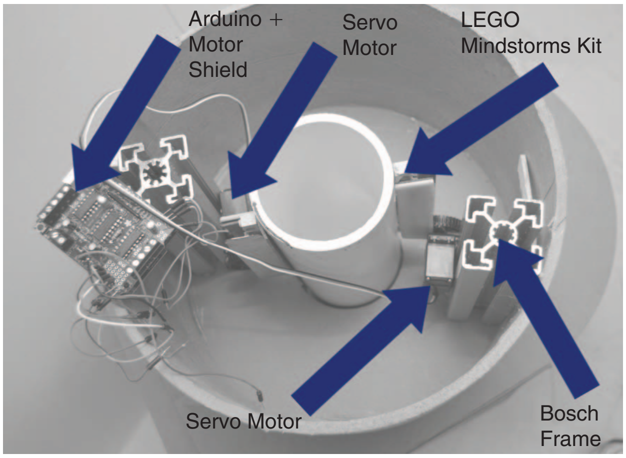


Figure 1. An example of architectural robotics: a wirelessly controlled rack and pinion system used to adjust the height of a table surface. (Photo courtesy of Anthony Threatt.)

one architecture student) to Ph.D. candidates (one architecture student). The students were assigned project partners and given the project theme, requirements, and execution time frame (one to two weeks were set aside for project conceptualization). The students were expected to brainstorm and come up with project ideas, which would be presented to the class. Upon satisfactory presentation of the aim, feasibility, and scope, the project would be given the go-ahead, with weekly progress reports and milestone demonstrations leading up to the final presentation. At the end of each project, the students had to upload project details, scenarios, images, videos, and source code to a dedicated class work group.

Articles and papers were assigned to be discussed in each class, typically alternating between architecture and robotics as subjects. The readings started with tutorials on definitions, research, and practices of architectural robotics ([12], [13], and [5, Ch. 4]) before delving into the more traditional aspects of both fields [14], leading to contemporary paradigms [15], and finally coming full circle to thoughts of the future and the integration of systems in an increasingly digital age [articles from *IEEE Spectrum Special on the Singularity* [16] (the authors can be contacted for a full list of articles)]. To further the collaborative environment, the students were asked to lead discussions on each article in the presence of the instructors. In addition to these discussions, the instructors taught introductory-level material in their respective areas, including multimedia presentations and videos, to give students a better idea of both fields. The students were graded based on discussion participation, project design, integration, and demonstration and closeness of projects to the proposed concept, although project deliverables were weighted heaviest.

Project Experiences and Summaries

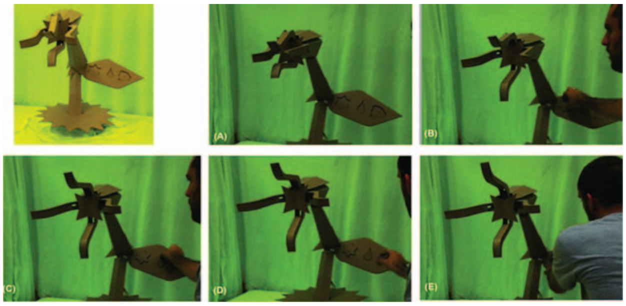
Each project had an overarching theme with goals to integrate the thought processes of both disciplines to find a balanced solution (details of the individual projects can be found in [1]). The aim of the first project from both the students' and instructors' perspectives was to familiarize everyone with Arduino and with one another. This was the shortest and least demanding project in terms of deliverables, but it was challenging due to the possibility of a culture clash in approaches.

An initial difficulty was due to the inherent differences in the meaning of the word *design* as understood by architects and engineers. Architects generally consider design to be a qualitative phenomenological experience appealing to the aesthetic sensibilities, while, to engineers, the word is a representation of a quantitative process for a specified performance-related goal focusing on functionality; the human factors psychologists' definition lies somewhere between these two. The instructors hoped that after the initial shock caused by students' contrasting expectations had subsided, the architects and engineers would work out an acceptable compromise, minimally sacrificing performance, or aesthetic quality.

Project 1 required a system design incorporating off-the-shelf toys to engage children, with no constraints on age group (LEGO blocks were used in the exemplary project in Figure 2), to force dialog between teammates. This allowed the students to develop relatively simple systems while exploring the capabilities of Arduino. This project was designed to create a relaxed environment to spark the creativity and collaboration of both fields. From the students' responses, it was found that this project represented a greater learning curve for architects than for engineers due to the limited exposure of architects to the concept of programming and sensor/actuator interfacing. While these projects demonstrated the ways in which robotics might actively support the physical environment, they still remained robots within environments. The intellectual growth was significant for the architects but not for the engineers.

The goal of Project 2 was to expand the range of possibilities, requiring the exploration of how robotics could augment existing architecture or provide a paradigm shift in architectural design. This project was meant to allow the architects to showcase their skills, specifically for urban disaster detection/management with no constraints on scope, scale, or components. These projects were more environmental than robotic, and therefore, the learning curve was greater for the engineers, as their systems were required to operate within the architectural envelope. The architects played leading roles, both in environmental analysis and, using knowledge gained from Project 1, selection of sensors and actuators for the scale models of the environments. The students reported that, in Project 2, there was a greater appreciation of one another's ideas, significantly less friction regarding approach, and less time needed for brainstorming compared to Project 1, which allowed for more time to develop and refine concepts.

The results (from the instructors' perspectives) were innovative and thought provoking. In contrast to the Project 1 efforts, the Project 2 visions (shown in Figures 3–6) literally expanded the environmental space at the cost of practical feasibility. With the exception of the directing leaf (Figures 4 and 5), it is difficult to imagine the technologies presented being viably and commercially scaled to the size of the



HENRIQUE HOUAYEK

Figure 2. Project 1—Interactive Flower: this project attempted to cultivate children's creativity by providing a hands-on interactive experience about the natural diurnal cycle of a flower while also helping them associate geometric shapes. Initially, in a closed-petal configuration, the flower opens up fractionally as an ingredient (geometric block) is correctly placed. The flower blooms fully when all three pieces are correctly placed and closes fractionally with each piece's removal, for immediate reuse. (Photo courtesy of Henrique Houayek.)

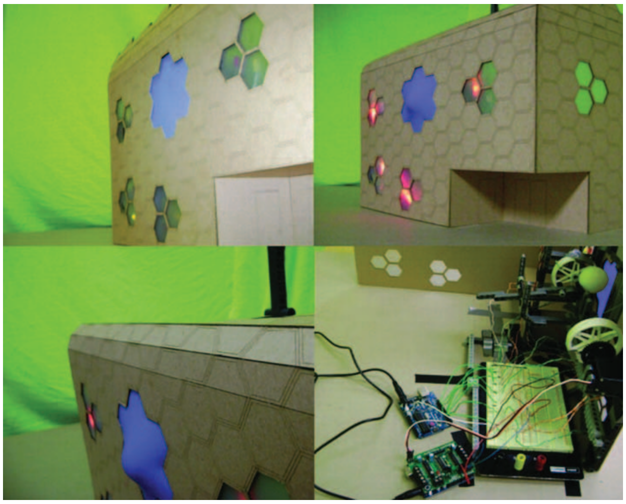

PAUL YANIK

Figure 3. Project 2—Shelter in a Storm: this project aimed to design building skins that could morph from conventional shapes to more aerodynamic ones to dissipate high wind forces such as hurricane winds. A wind-speed sensor would detect the presence of sustained wind gusts above a designated safe threshold, activating the morphing mechanism. The conventionally shaped building would then self-adjust components of its external surface to project a convex face toward the oncoming wind. The curved surfaces would dissipate the winds and thereby reduce the force on the underlying structure as with domed buildings and safeguarding the structure.


TAREK MOKHTAR

Figure 4. Project 2—The Directing Leaf: the leaf was designed to work with existing urban infrastructure in the event of tornadoes around or within city limits. In the event of a tornado sighting, the leaf would light up and point the population toward shelters and safer areas. A radio link to a receiver and speaker system would play area-specific warning messages to complement the visual aids. Upon relaxation of the situation, the leaves would return to their resting state and the speaker system would update the population. This system was designed to blend into the environment, though not inconspicuously, and was also capable of lighting up street blocks during festive seasons.

environments studied. Nevertheless, at this stage, the instructors noted that the architects were fully engaged and the engineers were perceiving the available architectural palette.

The next step was to challenge both disciplines simultaneously to create a fully synergistic system, a truly architectural robotics product. In contrast to Projects 1 and 2, Project 3 incorporated constraints, with feasibility as a consideration but not a necessity. More specifically, the projects (shown in Figures 7–10) were to be designed at the scale of a room or an apartment. This was an essential requirement as the theme of the project was "Aging-in-Place" [17]. The project was intended to generate ideas to ease a person's transition into aged care [18] to try to tackle a big global social problem.


TAREK MOKHTAR

Figure 5. Project 2—The Directing Leaf: schematic diagram of the leaf on trees on a city block.


JOE MANGANELLI

Figure 6. Project 2—The Particulate Control and Air Purifier (pCAP): added onto existing city infrastructure, pCAP was designed as an urban response mechanism to minimize the dispersion of airborne particulates and gases while providing shelter and purified air to those trapped within the noxious atmosphere. Augmented bus shelters would function as glowing beacons in the dusty haze, where purified air would be available. The pCAP used modified fire suppression sprinkler heads mounted on building parapets and actuated by gas and vibration sensors to produce atmospheric mist to trap the particulates.

This project was allotted the maximum amount of time (five weeks, as opposed to the two weeks given for Project 1 and four weeks for Project 2) to allow the groups to create complex environments, refine the mechanisms, and truly integrate their systems. It also resulted in the closest collaborations in the class, as noted by the students. The engineers freely suggested architectural innovations, while the architects were comfortable and confident in recommending sensing and actuation mechanisms, as evidenced by the students' oral conceptual presentations. Simultaneously, the students and instructors noted less time being taken for analyses as the semester progressed, with insightful comments from both sides on other students' subject matter.

The instructors found that, at a high level, the line between the two individual disciplines became increasingly blurred and the students ceased to be engineers or architects and simply became members of the group. The architects gained insight into robot modeling—kinematics and dynamics, sensor fusion, and algorithmic considerations—while the engineers

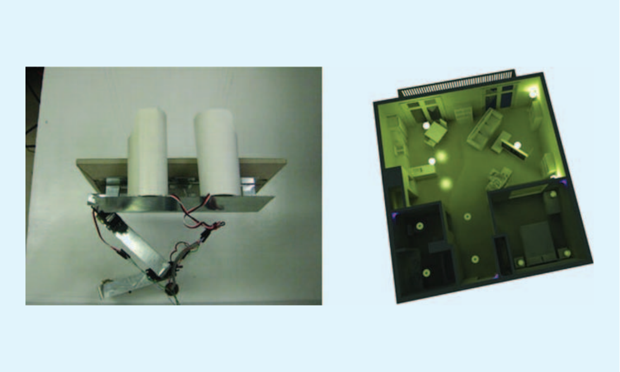

JOE MANGANELLI

Figure 7. Project 3—Redundant Robot Manipulator and Environment for ReLiS: ReLiS sought to automate heavy use and critical systems in living units based on the needs of occupants. It consists of a television mounted on a manipulator, which tracks the position of the occupant around the unit, while also providing position-based intelligent lighting based on the zonal location of the occupant.

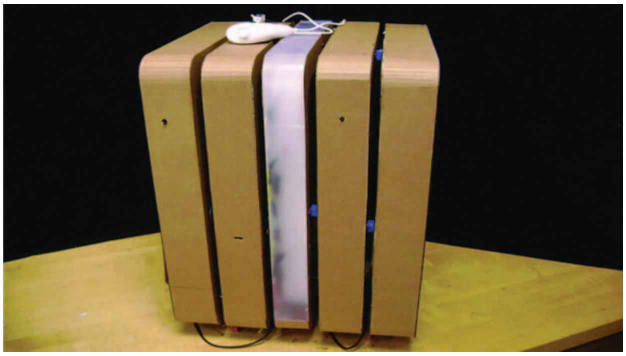

ADAM JAMES

Figure 9. Project 3—The mKare Side Table: the mKare is an interactive mobile unit built to aid the physically challenged in their daily lives. It was fitted with omnidirectional wheels, powered by servo motors, and controlled by a Wii remote to ensure movement in all directions. The sides provide sturdy flaps that rise up and extend themselves whenever desired, providing more workspace for daily activities while also keeping the overall size of the table compact.


TAREK MOKHTAR

Figure 8. Project 3—The Emotionally Together Armature (ET): ET consists of an overhead two-degree-of-freedom robot crane capable of motion along the length and width axes of a single room. A hanging armature picks up and deposits objects while using infrared sensors to avoid obstacles. ET was proposed with an option to minimize aspects of loneliness by analyzing the occupant's voice for emotional affect and then providing an automated response.


IVAN SILES

Figure 10. Project 3—Interactive Inflatable Furniture (IIF): addressing the difficulty for senior citizens in performing mundane activities such as getting out of bed or off of a chair, IIF aimed to increase the quality of life of both healthy elderly individuals as well as those with impaired mobility. Thus, the IIF was constructed of balloons overlaying a rigid three-link robot manipulator forming a chair that changes shape based on the preference of the user.

developed a greater appreciation for the incorporation of aesthetics and form into a system along with the composition of space.

All Project 3 designs, in one way or another, were about changing the shape of the human environment. These projects either involved applications/adaptations of robotics manipulator concepts or the mobile robot paradigm. Every project required user sensing and localization within the home setting. While the robotic technologies were not groundbreaking in and of themselves, it could be argued that the applications certainly were and that they could just as easily be applied to more conventional home or work settings. It is important to note that these environments were created from the ground up, with the robotic components already embedded in them (Figures 7, 8, and 10) as opposed being added to an existing architectural structure like in Projects 1 and 2 (providing ideas for 2) in Remark 1).

The outcomes of the collaborative process produced concepts of high potential. This is noteworthy due to the open-ended nature of these research problems, hinting that although high-tech devices and computers are now ubiquitous, robotics technology has not yet realized its potential in the home environment as it has in almost every other aspect of our lives [19].

Assessment and Evaluation

The evaluation of the success and impact of the class was made at several levels, most of which were qualitative or oral. From the instructors' perspectives, the class (and its successors) surpassed expectations in its primary goal of producing a group of graduate students who were well qualified to conduct research in architectural robotics. Of the eight students in this first class, four have completed Ph.D. theses in the area (three architects and one engineer) and one student is working on a technology closely associated with the architectural robotics paradigm. A similar ratio of students in subsequent classes has followed into research in architectural robotics, as highlighted in Table 1. In the fall 2010 and 2011 offerings of the class, the issue of having fewer nonengineers than engineers was mitigated by the presence of architecture students who had previously taken the class. These students served as teaching assistants, stepping in to work actively on some projects while simultaneously consulting on others. This interest and expertise has seeded and catalyzed the highly successful research program of the two class instructors over the past several years, including a multiyear grant awarded by the U.S. National Science Foundation to conduct fundamental research into robot environments for aging in place; the initial foundational ideas, research, and student involvement for this were laid during the initial class offering.

Throughout the course, some key fundamental research insights emerged. For example, in the third group of projects, the innovations in the robot mechanisms proposed were minor. However, the way the projects were deployed in the environment was novel, especially the interaction and communication with the people in it. The nontraditional use of lighting was particularly noted. This highlighted the point that architectural robotics is fundamentally about people.

Often, traditional architecture designs are beautiful yet sterile envelopes and the architect exits the process before or when people enter (and often wish to modify) the built environment. One important lesson from the class for the architects was that built environments ought to have a temporal existence based around the people who inhabit them. For the engineers, a key lesson was that robotics should be more than (and different from) the precise but insensitive instruments seen in industry. With people at the core of the design, the emphasis was placed on adaptability and compliance rather than precision and repeatability. Overall, the collective efforts of the class stressed the notion that simply bringing a complete robot, such as a humanoid, into an existing environment, the classical goal for roboticists, may not necessarily be the best solution. Instead, the notion of unpacking the humanoid and embedding parts of it appropriately into the environment, a key research concept that was expanded on in the research of the instructors [20], emerged during the course of this class.

While there was no obvious glass ceiling to shatter, the knowledge and understanding gained through this course are necessary for the advancement of both disciplines (architecture and robotics). Robotic technology is slowly developing toward ubiquitous domestic use, although the social and psychological implications for a robotic domestic space are not yet fully understood. In addition, the architecture and building industries are often slow adopters of cutting-edge technologies. While not a direct mandate, a part of the class directive is to hasten the fusion of architecture and robotics and simultaneously advance both fields.

By all accounts, the students found the experience of the class to be positive, especially considering that this was the first offering at Clemson University and not a requirement toward their degrees. They found the opportunity to collaborate with another department great and unique. In the students' own words, "the outcome of tighter integration as a result of the brainstorming sessions was generally achieved over the course of the class." It was noted that, in the final project, all of the students self-organized to further refine their ideas once the initial paradigms were developed. The students found that spending a significant amount of time outside the class working on the projects allowed them to learn from one another on the job and gave them a greater appreciation of one another's contributions and ideas. The students noted the usefulness of the idea evaluations before building each project, claiming that the "interim reviews to talk about the projects pushed the ideas about as far as we could take them." These reviews initially also served as arbitrations when the team members did not fully agree on the project design or needed to reduce the complexity. Almost no arbitration was required for the final project, while the first and second projects required some intervention to ensure that the scope and scale of the projects were achieved.

The students independently expressed surprise at the closeness with which they worked. Starting with the second project, they compiled unified lists of components and materials to be purchased. The work group created for the class was also noted to be helpful. While the instructors had access to the work group, it was primarily used by the students as a resource for sharing basic code, choices of components, materials, and refining of scenarios or ideas.

It was also noted that confidence in the course improved over time, and a suggestion (as yet unimplemented) that the instructors consider the potential of making this a two-part, year-long course, as opposed to the current single semester offering, was tabled. The positive experience affected enrollment (the class has since been highly oversubscribed), although, in addition to space and equipment constraints, the instructors believe that the dynamics of the class works best in a reasonably small group of less than ten students. This is not to say that a similar class cannot be successful if it is larger elsewhere with other instructors.

One weakness identified (and still an issue in the fifth holding of the class) is a lack of a suitable introductory text

Table 1. Students in architectural robotics offerings.

Class Offerings	Engineers	Architects	Other Disciplines	Theses
Spring 2009	4	4	–	5
Fall 2009	3	2	1	2
Fall 2010	5	3	–	1
Fall 2011	6	1	1	2
Fall 2012	3	5	–	N/A

for robotics. Existing texts are aimed at either the general public or engineering graduate students. We have not yet found an introduction to robotics suitable for a technically educated professional without an engineering background. Practical problems also resulted from the scale and hobby quality of the electronics used. Sensors and actuators were imprecise, poorly characterized, or underpowered, requiring ad hoc and time-consuming work-arounds to achieve the desired results. Partly due to this and the tight schedule, from the engineering perspective, the algorithms used were generally simple and open loop. Time was invested in postprocess documentation to highlight such difficulties to streamline the efforts of future students. In subsequent class offerings, this problem has been significantly reduced by having a graduate of the class serve as a teaching assistant. The student responses were also noteworthy in this regard, given that they all claimed to have put far more work into this course than their other courses. Some students even claimed to have worked longer hours for this course than any other course thus far, but, at the same time, they wanted more time to spend on the projects. This desire was only stated at the end of the course as the students began to reflect on their experiences. The students and instructors noted the lack of benchmarks for time frames in this regard, but this situation was rectified in future offerings.

Take Aways

In a short period, 15 weeks, students with very different backgrounds learned to work in unison with a common understanding. This resulted in new insight into the topic of architectural robotics and how to proceed when conducting research in the area. As the assignments evolved, what initially manifested itself as a problem was actually one of the greatest benefits of interdisciplinary collaborations: the inherent mismatch of the capabilities and purviews of the respective team members. Initially, teams struggled with the desire to develop a project idea without a full awareness of how each partner could use his or her skills to create a successful system. Notably, stressing on collaboration brought forth innovative results not attainable by either partner working alone. Some of the resulting projects cannot be defined as either architecture or engineering, but rather a productive, compelling hybrid of both—an architectural robotic system.

The field of architectural robotics promises to support and enhance human needs and desires. The gradual embedding of robotics throughout the built environment will, in the coming decades, have a broad social impact as these technologies sustain and, in some cases, augment everyday work, school, and leisure activities. This course served as an early effort for rising robotics engineers and architects to learn from one another in the process of dealing with a hybrid of their traditional concerns. It can be postulated that the buildings of tomorrow will be actively responsive to various external forces, including weather, security, and human needs. The expansion of one field into the other is inevitable and offers the potential for engineers and architects working together to advance human needs and desires and safeguard the environment.

Acknowledgments

This work was supported in part by an NSF Grant IIS-0534423. This article was presented in part at the IEEE International Conference on Robotics and Automation, Anchorage, Alaska, May 2010 [1].

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