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"Architectural Robotics": An Interdisciplinary Course Rethinking the Machines We Live In

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Abstract— **We discuss disciplinary barriers which have traditionally prevented robotics from significantly impacting the built (architectural) environment we inhabit. Specifically, we describe the implementation of, and lessons learned from, a multidisciplinary graduate-level course in Architectural Robotics. The results from class interactions and projects provide insight into novel ways in which robotics expertise can be effectively leveraged in architecture. Conversely, our outcomes suggest ways in which the knowledge and perspective of architects could stimulate significant innovations in robotics.**

I. Introduction

While major progress has been made within the core sub-disciplines of robotics over the past several decades, the transition of this progress into technologies affecting the world we live in has been relatively slow. Despite promising efforts in areas such as health care robots in the fields of surgery [1] (Chapter 52), [2], [3], rehabilitation [1] (Chapter 53), [4], [5], domestic robots [1] (Chapter 54), [6], [7], and robots for education [1] (Chapter 55), [8], robots are still largely restricted to industrial, remote, and hazardous environments [1] (Chapter 42), [1] (Chapter 47), out of view of most people. Robotics is still awaiting the "killer application" that will, as predicted in innumerable science fiction stories, make robotics widespread in people's everyday existence.

One engineered product familiar to all, though often overlooked by technologists, is the (architectural) environment we each inhabit. While architects have been increasingly incorporating new technologies into their methods and products [9], there has been almost no incursion of robotics into architecture, in the sense of the inclusion of robotic elements as integral parts of built environments. Architecture as a field has a long and rich history of innovation [10], and its economic impact vastly overshadows that of robotics. Widespread adoption of robotics technologies within architecture would likely have a major impact on our field.

Two highly desirable activities arise naturally from the above 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.

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This paper discusses each issue, via the experiences of the authors in a graduate-level course ("Architectural Robotics") at Clemson University, aimed at the intersection between Architecture and Engineering.

There is prior research combining robotics and Architecture. Mitchell [11] postulated that in the near future "our buildings will become...robots for living in". Most subsequent efforts have concentrated on either adding sensory/computational elements to existing architecture (smart buildings) [12], [13], or introducing self-contained robots into existing spaces, [1] (Chapter 55).The second approach appears to be the obvious way to introduce robotics into Architecture. However, we argue here that a more interesting (and more practical) approach involves a tighter coupling of the fields, in the sense of including robotics via (re)programmably moving the mass that forms the core shape of the environment.

The explicit goal of the multidisciplinary graduate-level course at Clemson University discussed in this paper is to explore the boundary between robotics and Architecture, and to promote creativity at the intersection. All course activities were designed to be "open-ended," with the creative process (rather than any specific end product) being the key object. As will be discussed in the following sections, this 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 engineers and architects in graduate classes [14]. A similar multidisciplinary course was also offered at the University of California at Davis [15], whose aim was to provide computer project experience to graduate students with very different education backgrounds. However, the course at Clemson University is unique in concentrating on the robotic elements being an integral part of environmental design (as is plumbing, air-conditioning, and other aspects of architecture), as opposed to being introduced into a previously (built) space.

In the following sections, we highlight some of the findings and results of the Spring 2009 Clemson course. The course is offered to students across all sub-fields of Engineering and Architecture. In this offering, enrolled were three Electrical/Computer Engineering and one Mechanical Engineering students, together with four Architecture students. Students were paired together in engineer/architect teams with each team engaging in three multi-week projects, the videos of which are searchable on Youtube using the project name. The team combinations were changed for each project to maximize the diversity of interaction. The experience of the students ranged from first year graduate students (two) to graduating Ph.D. candidates (one). In the following, the students, and the faculty who co-taught the course, summarize the highlights and the lessons learned.

II. Hardware Technologies and Components

Since the class was meant to be an intensive collaboration of architects and engineers, using Arduino as a platform was a natural choice. Arduino [16] is an open-source electronics prototyping platform based on an 8-bit microcontroller, popular in the field of physical computing. It uses a simplified version of the C/C++ programming language, created for individuals interested in developing interactive prototypes, who might not have the software skills or background to work on more sophisticated systems. Though simple, the Arduino platform is robust and extensible, allowing for the connection of sensors and actuators, as shown in Figure 1. Additionally, specific pins allow for the output of PWM signals, essential for servo motor control. Application-specific shield boards are also available to simplify the connection of multiple motors or audio devices.

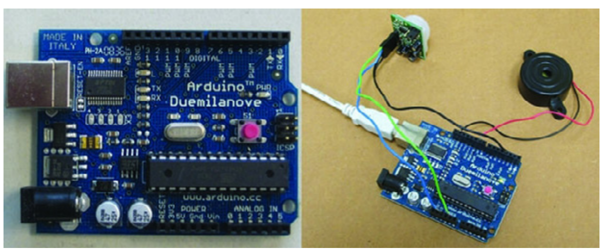

Fig. 1. Arduino Example

The Arduino can be programmed using a modified version of the C/C++ programming language, based on the "Wiring" project. Multiple scripts have been written to simplify coding tasks. The code editor uses multiple colors to differentiate parts of the user program, simplifying coding for users unfamiliar with programming environments. Additionally, the Arduino IDE, written in Java, provides a template for programmers to write their code.

These characteristics, plus its low-cost and ease of interface with off-the-shelf hobby parts made the Arduino an ideal platform for cross-displinary collaborative work. Students also had access to servos and stepper motors and a rich array of sensors, including pressure sensors, PIR and infrared sensors, switching systems, and relays.

In addition to the Arduino platform, sensors and motors, visualization software and rapid prototyping tools were used extensively throughout the design and development processes. The architects made virtual 3D and physical models using Rhino [17] and AutoCAD [18] as well as CNC laser cutters and milling machines. This process expedited critical analyses by the architects and engineers, allowing for quicker identification and mitigation of various technical challenges posed during the design and development stages.

III. Project 1: Children and Creativity

The groups designed systems to foster creativity and learning in children. The groups were required to interface a sensor and motor to the project board, allowing the students to explore the capabilities of the Arduino, as well as to hack an existing toy which could pique the curiosity of a child.

A. The Interactive Flower

This project attempts to cultivate children's creativity by providing a hands-on interactive experience about a flower's natural diurnal cycle. In addition, it helps children learn geometric relationships by placing puzzle pieces in their respectively shaped holes. The puzzle pieces are shaped in the form of the three basic ingredients needed to make the flower bloom: the sun, seeds, and water droplets. The flower is initially in a closed-petal configuration as shown in Figure 2 A. As each ingredient is added, an optical sensor detects its placement, noting that only the correct placement of a block triggers the sensor. Each placement causes the flower to open by a fraction of its totally-opened configuration as shown in Figures 2 B, C, D, and E. The flower blooms fully when all three pieces are correctly placed. As each piece is removed, the flower closes by the same fraction, eventually resetting to the closed configuration at which it started, allowing for immediate reuse.

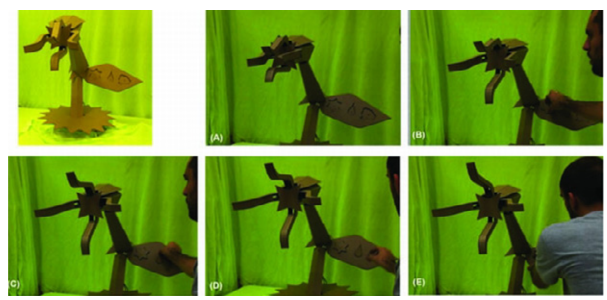

Fig. 2. Interactive Flower

B. The iTOI (interactive Toilet)

The inspiration for this device was a New York Times article highlighting the difficulties of trying to toilet-train young children [19]. The students figured that providing simple sensory interaction to the arduous process of relieving one's self could get toddlers to look forward to their next visit to the toilet. The iToi is an attempt as seen in Figure 3. Additionally, the device provides adults with information about the success status of the toddler's toilet visit.

The iToi uses off-the-shelf parts: a child toilet seat found at most department stores, proximity sensors, two servo motors, serving as toilet-paper and towel dispensers, and a sound box that activates music when the child is done. One proximity sensor detects the presence of the child when he/she sits on the kid toilet seat and additional sensors detect the success or failure of the visit. During successful visits, the sound box plays music to entertain the child and the two motors, initially at rest state under the seat, spins upwards, providing the child with toilet-paper and a towel.

C. Project I Summary

The overarching inspiration for Section III-A was to develop a device that is simple to construct, use, maintain, and move. Having such a device in a playground or the home could assist teaching children about the world around them outside the confines of a classroom. Additionally, the design and concept can be easily adapted into other tools that could explain various phenomena on the planet and the universe.

In the case of the iToi, the device provides sensory stimuli that entices the child into performing what is an otherwise cumbersome chore, a concept similar to [20]. While eliciting a few laughs, the iToi might be extended to new bathroom fixtures for aging-in-place the disabled. It should be noted that a video made to demonstrate this device was uploaded onto Youtube, quickly accumulating over 200,000 hits and receiving innumerous remarks ranging from indifference to disdain, indicating that such technologies, despite their altruistic intentions, can be intimidating if proper thought is not applied into it's form and function. However, these projects demonstrated the ways in which environmental robotics can support the physical environment being actively used for education (instead of being passively used only).

IV. Project 2: Urban Disaster Management

This theme explores how robotics can augment existing architecture or provide a paradigm shift in architectural design by focusing on disaster detection and management. No constraints were placed on the groups designs.

A. Shelter in a Storm

This project aims to design building skins that can morph from conventional shapes to more aerodynamic ones to dissipate high wind forces such as hurricanes winds. According to [21], the presence of curvature in the shape of building parapets reduces the wind speed traveling up the exterior wall surface and over the roof, thereby reducing the vacuum effect that typically occurs in more orthogonal designs, compromising the integrity of the envelope.

In this case, a wind-speed sensor detects the presence of wind gusts, which activates the morphing mechanism for sustained winds beyond a designated safe threshold. It is important to note that the morphing of the external structure does not affect the internal design, shape, and integrity. When high winds are detected, the conventionally-shaped building self-adjusts components of its external surface: the parapet walls, roof, and broad, flat wall surfaces over a reasonable and safe period of time, shown clockwise in Figure 4. Each of these vulnerable external surfaces flexes to project a convex surface towards the oncoming wind. The curved surfaces dissipate the wind and thereby reduce the force on the underlying structure as occurs with rigid domed buildings. After the high winds die down, the building reverts to its original shape. Additionally, lighting is used to outwardly project the current mode of the structure, and provides aesthetic beauty.

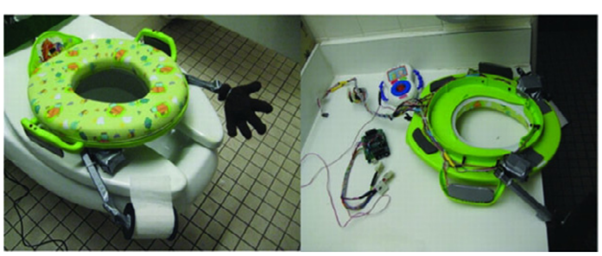

Fig. 3. The Interactive Toilet

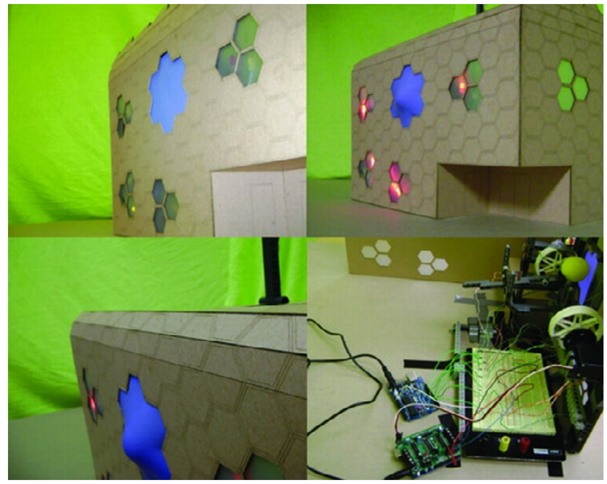

Fig. 4. The morphing shape of adaptable skin to reduce damage do to high winds.

B. The Directing Leaf

Tornadoes are extremely difficult predict, spot, and track, and cause widespread damage and destruction, especially in urban areas. The directing leaf works with existing urban infrastructure to guide and assist populations towards shelters and safer areas during tornadoes around or within city limits. It is a leaf-like device able to blend into the environment, though not inconspicuous, and is capable of lighting up street blocks during festive seasons as in Figure 5. The leaf itself is made up of a translucent material and embedded with high-powered LEDs which are visible from a distance as seen in Figure 6. It connects to the main branch (articulated out of a pliable copper plumbing pipe to match the color and texture of tree branches) by a stepper motor which turns the leaves from their resting state to point to the nearest tornado shelter or safehouse. Each tree outfitted with the "directing leaf" devices also radio-link to a receiver and

Fig. 5. Schematic of the Leaf on Trees on a City Block.

Fig. 6. The Leaf attached to a tree.

speaker system that is able to play area-specific warning messages from local weather centers, thus providing audio information to complement the visual aids. Upon relaxation of the "severe weather alert" status, the leaves return to their resting state and the speaker system alerts the population of a clear situation. Additionally, this device can be adapted for wildfire and lightning strike warnings and evacuations.

C. Particulate Gas Localization

In the aftermath of natural and man-made disasters, much loss of life and chronic illness results from exposure to air contaminated with hazardous particulates and noxious gases. The pCAP (Particulate Control and Air Purifier), added onto existing city infrastructure, is an urban response mechanism minimizing the dispersion of airborne particulates and gases while providing shelter and purified air to those trapped within the noxious atmosphere. Augmented bus shelters function as glowing beacons in the dusty haze, where purified air is available, Figure 7.

To minimize particulate dispersion, pCAP uses modified fire suppression sprinkler heads mounted on building parapets, actuated by gas and vibration sensors that produce atmospheric mist that traps the particulates. The demonstration includes a scale-model mock-up of a city block with a bus shelter fitted with an expanding cowl, air purification bellows and beacon lights. The mock up actuates by two servos responding to a puff of particulate released onto the model.

Fig. 7. Air Purifying Bus Shelter.

D. Project II Summary

Section IV-A provides a seed of thought as to how otherwise rigid structures can be reimagined to have more adaptable skin. To avoid the greater scale-up pitfalls involving implementation that inevitably arises, this project proposes only modifications to existing structures. The difference a curved surface makes in the protection of the integrity of a structure in the event of hurricane-force winds is surprising. Implementation seems relatively easy, even on existing structures, especially if only the parapets are to be made bendable. The logistical advantages this system provide are quite compelling. For example, in the event of impending hurricanes or tornadoes, it is very difficult to transport the sick, elderly, and disabled from institutions and assisted living facilities. This project provides a response to increase the integrity of the building structure by leveraging robotic technologies to provided a more cost-effective and adaptive solution to the challenge.

Sections IV-B and IV-C are examples of systems that can be added onto existing structures to provide response and relief. Simple prosthetic devices and off-the-shelf components can be innovatively put together to provide effective technologies. Additionally, the presence of Directing Leaves in trees and the Bus Shelter Bellows also provide a novel aesthetic in urban landscapes, useful for special events.

V. Project 3: Aging-in-Place

One of the biggest global social problems is the support of those with short- and long-term disabilities and whose mental or physical health is in general decline. An increasing number of the aging prefer living independently, and resist moving into institutional care facilities [22]. These projects provide ideas for delaying the first step away from the family home, or ease the person's transitition into aged care [23].

A. ReLiS - Responsive Lighting and Screen mount

ReLis is an intelligent home environment for heavy-use appliances to anticipate the needs of occupants. The main component of ReLis is a 3-link revolute planar redundant robot manipulator, Figure 8, which follows the occupant's position while avoiding obstacles and furniture, orients the media center display mounted on the end-effector in their direction. In addition, the lighting system adjusts lamp intensities, based on the occupant's location and time of day, alleviating the need for fixed switching systems. The model presents a prototypical single occupant one-bedroom unit with a combined living room/kitchennette, as shown in Figure 8. A tracking algorithm adjusts orientation and lighting intensity based on pre-defined zones of the occupants location, optimizing robot travel, intrusion, obstacle avoidance, and power consumption.

Two PIR sensors mounted on top of the screen provide a binocular comparator that centers the screen end-effector towards the occupant. The lighting works in conjunction with the redundant robot by adjusting light intensity based on occupant location. The project also calls for a universal remote control device to allow for occupant response override.

B. ET - Emotionally Together

Loneliness is a common problem for the aged. ET minimizes aspects of loneliness by analyzing voice for emotional

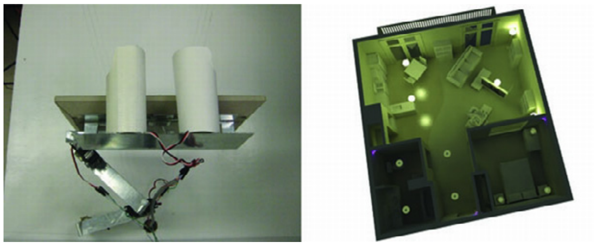

Fig. 8. Redundant Robot Manipulator

affect to provide an automated response. The robot detects four distinct emotional states: happiness, sadness, anger, and fear. In each case, the robot provides personalized sensory stimulation through lighting color, ambient music, and the social affect of its motion.

ET is an overhead 2-DOF robot crane capable of motion along the length and width axes of a single room shown in Figure 9. A hanging armature picks up and deposit objects while using infrared sensors to avoid obstacles. When an obstacle is detected, the robot recalculates it's motion by assigning high cost to the obstructed directions. If no navigable trajectory is available, the robot stops.

Fig. 9. The ET arm

C. *mKare - Intelligent Side Table*

The mKare, shown in Figure 10 is an interactive mobile unit built to aid the physically challenged in their daily lives. It equipped 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 amd extend whenever necessary, giving more workspace for daily activities while keeping the overall size of the table compact. A smart lighting system turns on in the event of insufficient ambient light or as a nightlight.

D. *IIF - Interactive Inflatable Furniture*

Even with ubiquitous digital technology, domestic environments remain comparatively low-tech and conventional, neglecting human conditions, especially for aging-in-place. Increases in lifetime expectancy require special care and spatial conditions. For most senior citizens, mundane activities such as sitting, sleeping and getting up can be difficult. IIF increases the quality of life of both healthy elderly

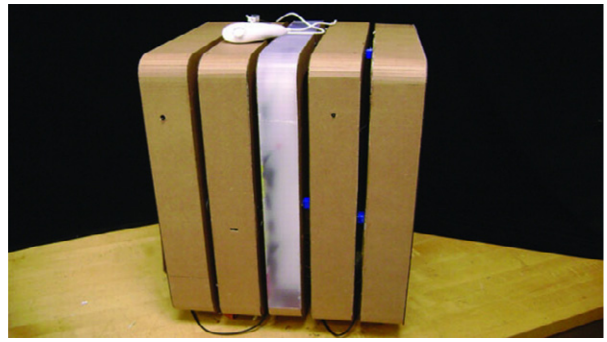

Fig. 10. The mKare Side Table

individuals as well as persons with impaired mobility. It is constructed of balloons overlaying a rigid 3-link robot manipulator forming a chair that changes shape based on the preference of the user. For the prototype, the balloons inflate using small $C0_2$ canisters. The prototype in Figure 11 shows only the body of the IFF, since its shape is lost under the balloons.

Fig. 11. Interactive Inflatable Furniture

E. *Project III Summary*

Three of the four projects associated with this theme involve applications or adaptations of robotic manipulator concepts. All of the projects require user sensing and localization within the home setting. While the robotic technologies are not ground-breaking, it can be argued that the applications certainly are and can just as easily be applied to more conventional home or work settings. The particular choice of strategies and materials resulting from the collaborative process produced concepts of high potential. This is noteworthy due to the open-ended nature of these research problems. This hints that while high-tech devices and computers are now ubiquitous, robotic technology has not yet realized its potential in the home environment as it has almost every other aspect of our lives, and echoed by [24], [25], and [26].

VI. Lesson Learned

With each assignment, what occasionally manifested itself as a problem was actually one of the greatest benefits of interdisciplinary collaborations: the inherent lack of understanding of the capabilities and purviews of the respective team members. Often, teams struggled with the desire to develop a project idea without a full awareness of how each partner could bring their background and skills to bear on the success of the project. Notably, the stress of collaboration brought forth interesting results, not attainable by either partner working alone. In fact, some of the resulting projects cannot be defined as either architecture or engineering, rather a productive, compelling hybrid of both.

Practical problems 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 workarounds to achieve the desired results. Time was invested in post process documentation to highlight such difficulties in order to streamline the efforts of future students. While there was no obvious glass ceiling to shatter, the knowledge and understanding gained through this course is, arguably, necessary for the advance of either discipline - Architecture and Robotics. Robotic technology is slowly developing towards ubiquitous domestic use, although we do not yet understand the social and psychological implications for a robotic, domestic space. Additionally, the architecture and building industries are often slow-adopters of very new technologies.

For Architecture and Robotics, the collaborative research assignments of this novel course cultivate new vocabularies of design and engineered systems as needed to respond to human needs and wants, developing reconfigurability, reliability, controllability, and usability theories. From Robotics, Architectural Robotics will require sophisticated algorithms for sensing and inferring the occupants' activities, and the external conditions of a building that trigger reconfiguration, as well as planning and routing. For Architecture, the course contributes to an understanding of how to apply new technologies to improve evermore complex buildings. For faculty members in both disciplines, the course poses questions of pedagogy such as: "How to educate students from these different backgrounds to collaborate productively in teams?" and "What tools could further teaching and learning in the design and implementation of Architectural Robotics?".

VII. Conclusion

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 reckoning 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. Thus, the expansion of one field into the other is inevitable and offers potential for Engineers and Architects working together to advance human needs and desires and safeguard the environment.

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