Configurable Space: Architectural Robotics at the Scale of Furniture

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A thesis submitted in partial fulfillment of the requirements for the degree of:

Master of Science in Architecture

University of Washington
2017

Committee:

Brian R. Johnson

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Program authorized to offer degree:
Architecture

University of Washington

Abstract

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The subject of architectural robotics is an important contemporary issue that urges effort of investigation and understanding in a changing technological world. The Digital Revolution, which is the shift from analog and mechanical to digital technology with the proliferation of the computer and Internet, has brought many great possibilities of interaction among people. However, this advance in digital, ubiquitous and interactive technology has not rendered deep changes in architecture yet. The built environment still is inelastic and unresponsive to people's input. In grappling with this issue, this paper broadly investigates the subject of architectural robotics, highlighting the current stage of development of the field, and stipulating the reasons for the recent growing interest in it. This paper also explores the stimulus and causes of architectural robotics, points out the key elements of this subject, and examines several types of built environment adaptation. The great part of this paper, however, documents the process and analyzes the result of an empirical study conducted to explore new opportunities of architectural robotic at the scale of furniture. In this study, I introduce and describe a novel, intelligent and networked suite of robotic furniture, which aims to work as an assistive technology to support aging in place. I present the design and construction of this robotic suite composed of two robotic furniture elements – a chair, which supports lifting; and a screen, which transforms the space and provides various activities within the same location. The thesis also reports on an initial experiment with a senior volunteer, evaluates the two robotic furniture items, and proposes future directions for investigation.

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Introduction

Recent technological advances have changed the way people interact with each other in a given space, and also the way people interact with the space itself. The incorporation of digital and intelligent technology into the built environment promises to further impact the human-environment relationship. Architectural Robotics, in this context, is an area of study that investigates how the integration of responsive technologies into the built environment changes the interaction between humans and space. In is important, however, to reveal and discuss some important underlying premises that many times are not considered when investigating the human-spatial-computer interaction in architectural robotics.

It is known that human needs vary through time, and this implies adaptation of the surrounding environment to adjust to these changes. However, unlike the variability of human needs, the built environment is traditionally inelastic and unyielding. The conflict between the elementary natures of these two entities is a fundamental issue that every architect and human-centered designer needs to deal with when designing objects and spaces for human use.

In the case of architecture, it is necessary to understand the traditional relation between the space and the function it houses. More specifically, regardless of the driving force – form following the function or function following the form - the constructed mass (i.e. structure, envelope and roof) is created to safeguard the existence of activity performed in the space. A bathroom, for instance, has purposes different than a kitchen for attending to different human needs. While the former is designated to body cleaning and alleviation of physiologic necessities, the later basically is a place for the preparation of food.

The idiosyncrasies of these two activities impose different requirements, which are complied with through two distinct forms. These activities, thus, cannot be properly performed out of their own designed space, and consequently, they require that users move from one place to another in order to fulfill their temporal needs. There are some difficulties with the condition presented above, though, ranging from the lack of available space in a growing urban world to the reduced capacity some people have (e.g. disabled and elderly) to move around.

As a response to the conflict highlighted above between the inflexibility of the built environment and the ever-changing needs of humans, architectural robotics aims to actively support inhabitants, adapting to their temporal needs and desires through physical reconfiguration. Relying on the example provided before, it is difficult to imagine a kitchen transforming into a bathroom; however, it is a plausible proposal having a living room becoming a bedroom (or vice versa).

The Revival

The capacity of robotics as a field has advanced consistently in recent decades, and nowadays we can see its application in many areas. For instance, in medical settings, robotic arms increase surgeons' freedom of movement, allowing more dexterity. Also, robots are used extensively in aircraft and automotive industries for manufacturing. Although interest in robotic architectural environment starts in the 1960s with Archigram's vision [1], it isn't as widespread today as interest in other areas; its implementation has been largely limited to elevators, escalators, automatic doors and other flimsy components. Perhaps the unexploited application of architectural robotics is due to the narrow understanding of robotics by architects, the consequence of which is limited adoption of the technology and failure to translate it into architectural purposes [2].

Figure 1 – Archigram's Walking City

Interest in architectural robotics has been growing recently, although it is still in its embryonic stage. Future explorations will solidify robotics in architecture – though there are many questions involving the key elements of this field, the grammar and vocabulary for architectural practice and, of course, the educational opportunities [2] [3]. Nevertheless, we can see today robotics applied meaningfully in buildings such as St. Gallen, by Santiago Calatrava [4] and the Olympic Tennis Centre, by Dominic Perrault [5].

Other evidence that reinforces the assertion of escalating significance of architectural robotics can be found in the growing number of courses orientated to exploring animated architecture. TU-Delft's Hyperbody (Netherlands) [6], IAAC (Spain) [7], and Cornell's Architectural Robotics (USA) [8] are some of the research groups conducting forefront researches and remarkable projects in this field.

The reasons for the revivification of interest in robotics is not completely clear, but perhaps one of the crucial factors is that associated technology has become more accessible to architects and designers [9]. Physical computing, one of the key element in robotics, is easier to operate and cheaper to acquire. For instance, simple kits containing a microcontroller plus several other pieces to assemble (e.g. actuators, sensors) can be purchased for less than $100. Also, there are several computing programs available to designers, such as SolidWorks[10], Grasshopper[11] and Firefly[12], that are highly valuable when simulating physical geometry interaction.

So far, this paper has provided a background regarding the underlying premises needed for investigating human-spatial-computer interaction in Architectural Robotics, and a brief history of the subject. The following section, however, reviews works of some important researchers in order to develop theoretical principles to ground the empirical study that will be presented ahead.

Integrating computing into the built environment as new way of human-spatial interconnection

In his book Oungrinis [13] examines the topic of architectural robotics, responsive environments, and the impact of information technology on the relationship between people and the built environment. He argues that many recent technological advances have been disconnected with the built environment.

Ougrinis' book goes in the same line as Michell's [14]. In fact, the two works have a high degree of similarity in analyzing the human-spatial-technology relationship and its effect. In Mitchell [14], the author points that technological advances (among other aspects) drive social changes in spaces. The recent technological advances, however, have not been successfully thought through and articulated by designers yet. Mitchell believes that the solution to this issue involves the meaningful integration of technology in the built environment in order to “create fresh urban relationships, processes, and patterns that have the social and cultural qualities we seek for the twenty-first century” [14]. The author speculates how various types of technology might be incorporated in the built environment to support humans’ necessities.

An important aspect concerning the role of architecture and technology toward people’s interaction is discussed by Pask [15]. He argues that architecture and cybernetics have a similar root, and that architecture is an area that is concerned with designing of systems rather than simple physical entities. In designing these systems, (cyber-physical) designers will be concerned not only with the architecture itself, but also with ways to use this architecture as means to organize and control diverse entities (i.e. humans and nonhumans) in order to (a) achieve the idealized interplay between them and (b) provide humans assistance to their salient needs. Pask believes that it is necessary to understand the interdependence of humans and the physical surrounding they are situated in order to fulfill these two points. In this respect, Pask introduces the concept of ‘mutualism’, where each entity (including the built environment) has power to influence the other. The author also speculates that it is possible to augment the mutualism by embedding computing into the built environment to create what he calls a “reactive environment”.

Following Pask's line, Easterling [16] elaborates what she thinks is the future of architecture in an era of ubiquitous computing. In this heavily theoretical article, the author highlights the human-technology and human-space interconnection, and argues that all three of these entities have what she calls 'disposition', which means the capacity an entity has to act. Architectural entities, in this sense, would have a disposition or a capability to actively influence the way others entities behave. Here, the author gives the notion that active object (i.e. architectural) also "governs" the way other entities (i.e. humans) interact each other. Designers, therefore, will design an active entity with agency and capacity to drive the way people interact with each other.

Theoretical principles

Two important principles are drawn from the literature reviewed above– (a) the relationship between people and the built environment is bidirectional, and (b) embedded computing can serve as a means for augmenting human-environmental interplay. The first principle indicates a symbiotic and synergetic interconnection between people and the physical space in which they are situated. In this relationship, both people and the physical space have capability to influence and be influenced.

The second principle puts forward the idea of embedding computing into the built environment as a means to augment the relationship between humans and physical space. The double elementary human-spatial relationship is turned into a human-spatial-computing relationship, where "the dialogue (between inhabitants and the physical space) can be redefined and extended with the aid of modern techniques" [15]. The principle draws the idea of a responsive and adaptable environment that senses, processes and responds, augmenting people's 'agency' in the in physical space.

Architectural robotics key elements

Although architectural robotics is in its initial stage, we already can perceive common points in many projects in the field. Essentially, there are three key elements that constitute architectural robotics base. The first one is the adaptable architecture, which regards the different stages of environmental condition. Adaptable architecture is strictly related with the built environment adaptation types described in the next section (i.e. accessibility, acoustics, weather comfort and spatial transformation). In the Pop Up Apartment, for instance, each of the four predetermined arrangement has different space, functions, circulation, openings and architectural elements [17].

Changeable architecture will guide the second element, the transmutable geometry. This one is associated with ways by which the changeable architecture will be achieved (e.g. folding, sliding, expanding) and means (pneumatic, mechanical, chemical) [17].

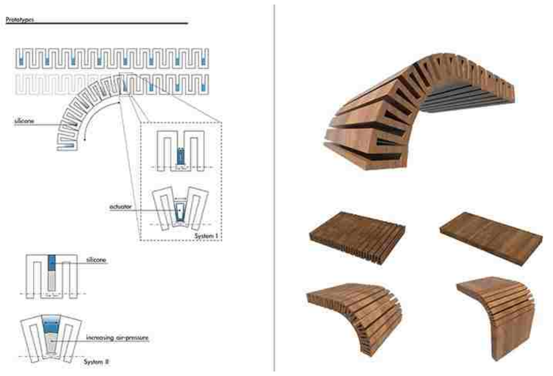


Figure 2 - Groundfloor by Beagle - Pneumatics as mean to fold

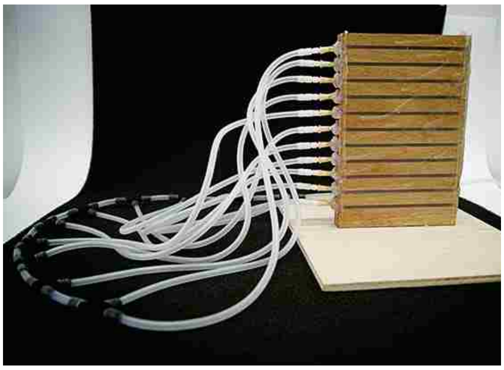


Figure 3 - Groundfloor prototype

The last architectural robotics element is the embedded computing – the computer system, composed of microcontrollers, sensors and actuators, that is responsible for controlling the transmutable geometry. Embedded computing can be divided into three basic types of control– direct, procedural, and supervised procedural. The first is the simplest control type, as it uses only sensor and actuator. The second one has sensor and actuators as well, but there is also another element that adds complexity to the control system, which is the microcontroller. Finally, the last one is similar to the second, but it will reevaluate its own action on every loop as it senses the consequences of its actions on the environment [17].

Stimulus, Causes and Applications

Architectural robotics provides opportunities to explore the built environment's physical reconfiguration in various contexts, such as accessibility, acoustics, weather comfort, and spatial transformation, among others. Some of these applications look quite naive, while others seem loftier.

Accessibility is one of these easy applications of robotics, and this involves the replacement of conventional doors for automatic ones that sense the approach of people. The Metro Station by Arte Charpentier [18] and Alcoy Community Hall by Calatrava [19] are two examples of fancy design for a rather simple purpose – see Figure 4 and 5.

Figure 4 - Alcoy Community Hall

Figure 5 - Metro Station

For acoustic purposes, moveable facets and/or transformable envelope elements could alter the sound vibration and transmittance, adapting the space to the different kinds of acoustic requirements. Manta, by Belanger et al. [20] and Resonant Chamber, by RVTR [21], are two visually attractive examples – see Figure 6 and 7.

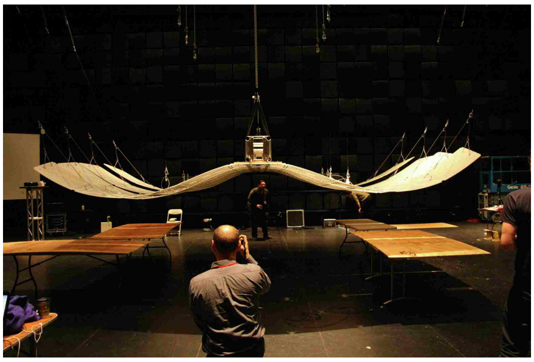


Figure 6 - Manta

Figure 7 - Resonant Chamber

Architectural robotics projects involving weather comfort aim to control temperature, humidity and solar intensity, among others, in order to maintain environmental conditions within human comfort zones. The Air Flow(er), by Lift Architects [22], and Kiefer Technic Showroom, by Giselbrecht [23], illustrate this robotic application in weather control – see Figures 8 and 9.

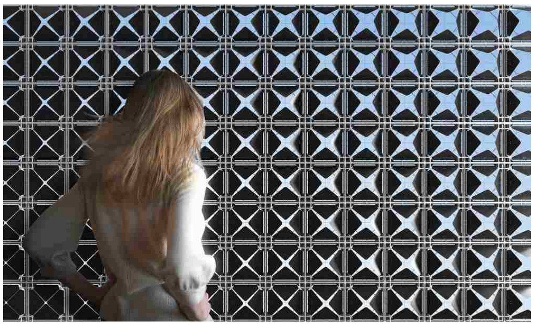


Figure 8 - Air Flow(er)

Figure 9 - Kiefer Technic Showroom

Although the explorations identified above are intended to serve humans, they do not establish interactive relationships between the architectural robotics elements and users. For instance, the use of robotics in environmental control does not have direct communication with human occupants, but from the environment itself. Likewise, there is no direct information exchange between users and architectural robotics systems for acoustics purposes. These two architectural robotics applications do not consider any direct input from users other than simple indication of constraints, such as the set up for desired temperature.

On the other hand, there are other architectural robotics applications that are associated with loftier goals. For instance, the issue of mass urbanization is a delicate one – most countries have experienced (or are experiencing) a massive migration of people from rural areas to urban ones. This is an issue that concerns not only developed nations but the entire world.

In this scenario, one of the primary quandaries involving architecture and urban planning is the limited space available in urban settings. Many cities fail to expand urban infrastructure to fulfill demands of an increasing population. When well applied, the strategy of concentrating more people per square foot seems to be a valid proposition – the high per-person costs of urban infrastructure are reduced when more people come into the "equation". However,, the reduction of dwelling units' floor area is a negative side effect of this concentration.

In response to this mass urbanization scenario and to density problems, architectural robotics could provide six compelling arguments – (a) diversified typology, (b) maximized spaces, (c) traffic reduction, (d) gas emission reduction, (e) material economy, and (e) investment optimization. All propositions are based on the idea of compressing one or more functions in the same space; this idea implies modification of the physical space to support these different activities. Colani's Rotor House [24], Hyperbody's (TU-Delft) Pop Up Apartment [6], and Greg Lynn's RV House [25] are all good examples of this – see Figure 10, 11, 12, 13, 14 and 15.

Figure 10 - Rotor House - three stages

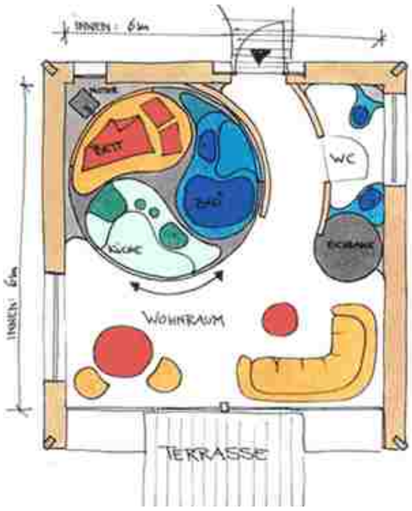


Figure 11 - Rotor House - plan

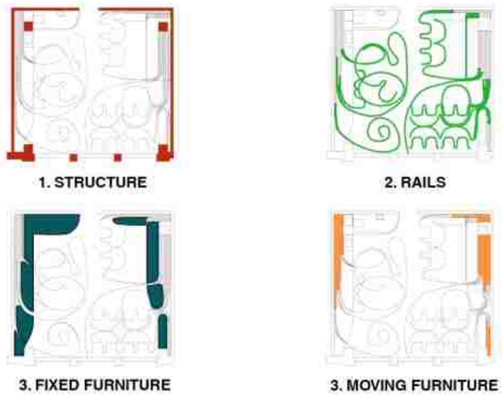


Figure 12 - Pop Up Apartment - plan

Figure 13 - Pop Up Apartment - prototype

Figure 14 - RV House - Prototype

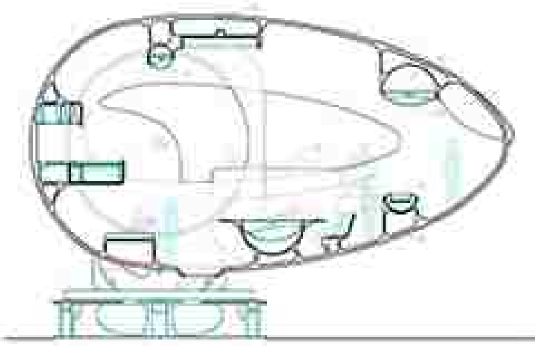


Figure 15 - RV House - Section

Research Motivation

Similar to the problem of urban mass migration, the subject of aging in place is an important contemporary issue that urges effort of investigation, understanding and creative design responses. According to the National Institute of Health (NIH), there has been a tenfold increase in the American population at the age of 65 or more in the last century. The life expectancy in the United States almost doubled in the 20th century. The number of centenary people in the USA was about 3,000 by 1950 but projections now suggest that this number could reach one million by 2050 [26] [27].

As people grow older, it is inevitable that their cognitive capabilities and mobility decline. This fact often forces seniors to either move from their homes to expensive care facilities or have family members take care of them. However, the great majority of people want to grow older in the comfort of their own home, a phenomena known as aging in place [28].

This scenario urges responses to support seniors in their daily activities and extend their independence in their own home. There have been several responses using technology to support elderly people in their daily activities. Most of these responses, primarily working as assistant caregivers, involve the use of electronic devices to observe, supervise and record seniors' health condition.

Nevertheless, the built environment could afford more than just electronic health monitoring. There are great opportunities not yet fully explored regarding the active support of seniors' daily activities.

As a response to this phenomenon of aging in place, researchers at The Clemson University Institute for Intelligent Materials, Systems and Environments (CU-iMSE) have developed the concept home+, containing a number of 'networked and distributed robotic furnishings' [29] [30]. Over the course of several years, CU-iMSE researchers have developed projects (e.g. Assistive Robotic Table – ART [31]) that aim to respond to this issue considering more than just monitoring health, but activating mass and animating form. The study presented in this paper, which shares similar motivation and is influenced by home+ vision, presents the design and construction of a suite of furniture – chair and partition. The method, design and fabrication process is described in the following sections.

Method – Research though Design (RtD)

Following from the considerations made so far, and following the direction the literature suggests - integration of technology into the built environment - this paper describes a study that aimed to understand how a responsive, cyber-physical environment could support aging in place.

The project consisted of developing a pair of responsive, cyber-physical artifacts – networked furnishings - that aim to empower elder users by giving them lost physical (and potentially psychological) capabilities. Research though Design (RtD) [32] strategies were used to generate the networked furnishings, using multiple iteration and evaluation to elaborate more precisely the needs and the respective affordances associated with the needs.

In this process, the study included a co-design element (using design engineering graduate students at Clemson University) that aims to add new aspects (specially technical) to the project. Physical model fabrication of the developing design concept was done, and tests were conducted to inform consecutive iterations. The following step of the study involves the fabrication, installation and testing of a full-scale prototype in a laboratory setting. This setting enabled an experiment to measure how supportive the designed artifacts actually were.

The Chair

The primary objective of the chair is to support a person with limited strength to get up and sit down, reducing the exertion required to carry out either action. The first design conception consisted in a continuous sheet composed of multiple materials. This combination of rigid and flexible materials would allow bending at a specific point to achieve the shape needed. In more details, the idea was to use rigid material at the seat and at the back, and flexible material at the joints. The physical transformation of the chair's shape would occur by bending these two joints, as depicted on Figures 16, 17, 18 and 19.

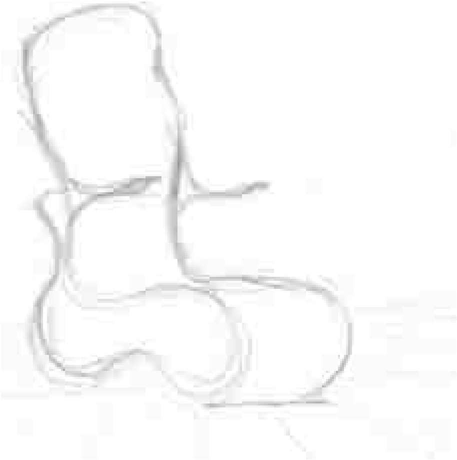


Figure 16 - the chair's first concept consisted on a continuous sheet

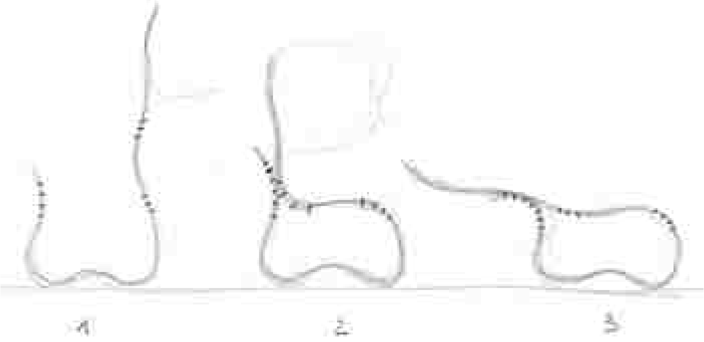


Figure 17, 18 and 19 - the idea was to have three different stages

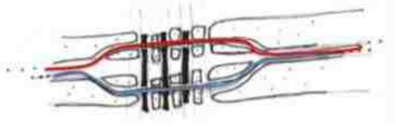

Figure 20 and 21 - The chair supporting sitting and getting up

Several model studies were constructed in order to test the design conception and the mechanical system of this approach. The first study model consisted of a 2x6 inch piece of flexible foam, scored at specific locations to facilitate bending at these points. It used monofilament-fishing line, run through the foam, as tendons. When the cables were pulled, the foam would bend – see

Video 1 and Figure 22. This simple model rendered animating results and inspired me to make further experimentation.

Figure 22 - cables 'running' through the foam

In the second model, I intended to have the cables ‘running’ at the perimeter of the foam in order to optimize the result – because the further the cables are from the foam cross-section’s geometric centroid, the easier it is to bend. Several pieces of foam and laser cut acrylic were used to construct this experimental model – see figure 23 and 24. The acrylic components were located specifically at the places that I wanted the bending to occur. The cables ran through small holes located in the laser cut acrylic pieces – See Video 2. Once again rendering promising results, I decided to fabricate a third model considering the whole shape of the chair.



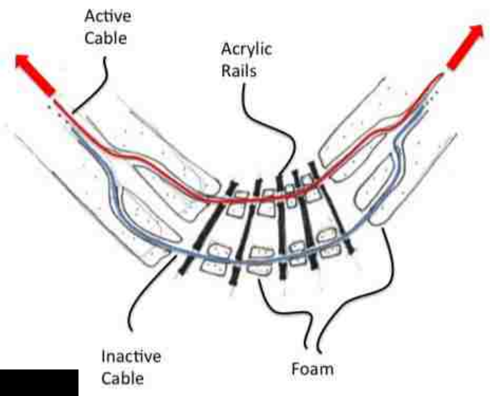


Figure 23 and 24 - experimental model scheme

For the third prototype, I intended to find design solutions to hide the cables and other protuberant pieces that would obstruct a person to sit and lay on the surface of the chair. The mechanical components needed to be embedded in the chair in such a way that the chair would permit a person to sit on a flat and smooth surface. Having this consideration, it was proposed to establish two sets of layers where the cables and the acrylic rails were placed inside the chair shape in order to avoid seating obstruction. A flat surface would permit a person to sit on the seat and to lay back against the chair back without any physical obstruction – see Figures 25, 26, and 27. However, this conception failed because of the considerable friction between the tendons and the acrylic/foam.

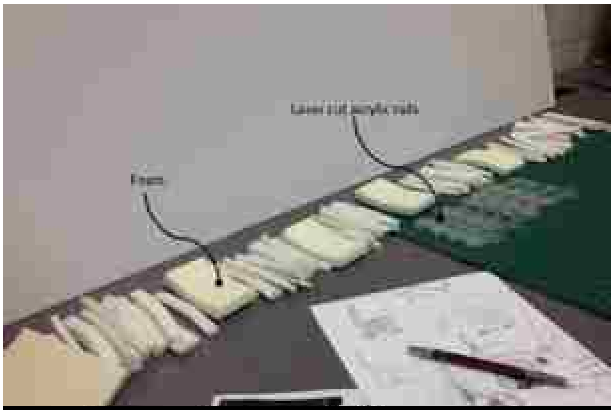


Figure 25 – Components for the third prototype

Figure 26 - Components assembled

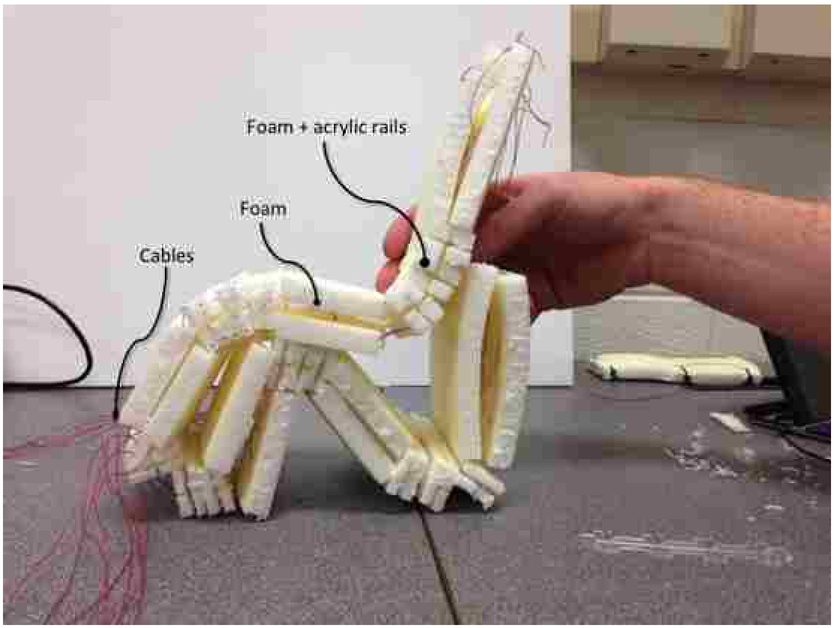


Figure 27 - Third prototype's final shape

In the end it was decided to move from these early attempts to another design alternative, more pragmatic and of simpler realization. As Figure 28 shows, the new design concept consisted of a rigid structural frame built out of extruded aluminum sections and wood. Four linear actuators were planned in this rigid frame as a way to achieve transformation of the chair's overall shape. Further modifications were made in this design conception as a way to solve technical issues and to achieve desired geometry.

Figure 28 - Chair

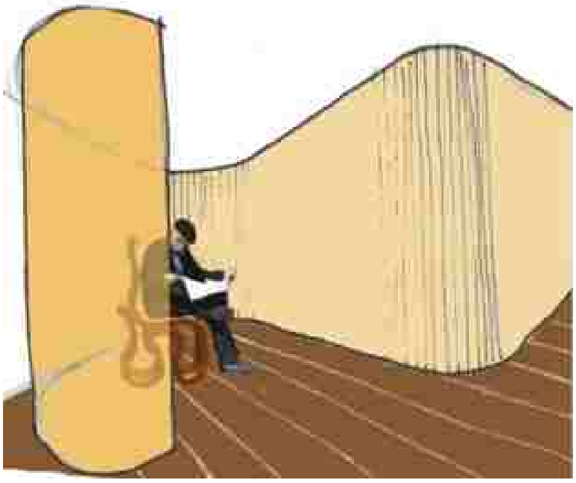
These modifications resulted in greater stability to the overall shape and improved ergonomic aspects. Although the early version was not fabricated and tested at full size, it seems that the geometrical modifications pointed out above yielded better performance of the linear actuators. In this final prototype, it was possible to use three linear actuators instead of four. The amount of force produced by them is enough to raise and lower an adult person with no difficulty – see Figure 29 and Video 3.

Figure 29 - The chair assisting a person to stand up

The Screen

The second element of the robotic furniture ensemble was a space-making one, rather than the place-making chair. The main goal of the screen, or partition, was to create different spatial configurations to support several functions in the same space. Furthermore, I visualize the partition as a physical support for many components that are normally installed on walls, such as TVs, frames, and bookshelves, among others. The partition is an adaptable and robotically reconfigurable architectural artifact that transforms the space, supporting elder users in various activities within the same location – See Figure 30.

The design of the partition was derived from the early investigation of the chair. The original basic design conception of the chair – a combination of rigid element for the seat and back, and flexible elements for the hinges, with activated cables - was adapted and used to fit the partition purpose. A corrugated plastic was substituted for the rigid parts of the foam, and tube hinges substituted for the layers of scored foam and laser cut acrylic. The cables continued to be considered as a way to actuate the different parts (i.e. panels). The expected behavior of the early study model successfully proved the mechanical conception - see Video 4.



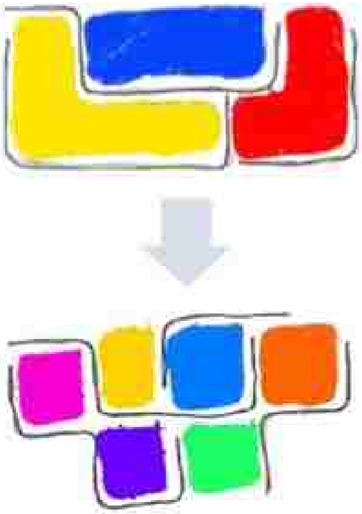


Figure 30 – Design concept

This basic design conception was further explored in a second (full size) model. The idea was to have a modular system primarily composed of panel, tube hinges and actuators. – See Figure 31 and 32.

Figures 31 and 32 - Wood frame covered with corrugated plastic

The panels were made of wood frames covered by corrugated plastic sheet; each panel was mounted on a ball caster to permit movement. Following the same design conception of the first prototype, the tube hinge was composed of four PVC tubes that are gathered together by a flexible cable – See Figures 33 and 34.

Figure 33 – 4-tube-hinge

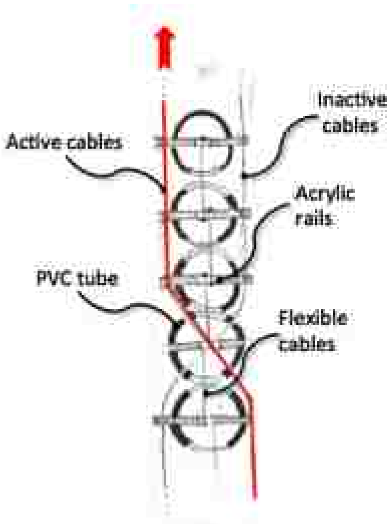


Figure 34 - 4-tube-hinge detail

Two tendons were used to transmit the movement from the motor to the panels. The tendons ran across the panels through the wood frame, and through holes in the acrylic pieces installed at each of the four-tube hinges. As Figure 33 shows, the four-tube hinge is able to create a rounded corner, permitting the two panels to fold all the way back on themselves when one of the sets of tendons is activated.

Despite the high level of elaboration, this configuration had some issues. First, it was not possible to rotate each panel independently; second, the force placed on the tendons was too high, resulting in regular ruptures. The replacement of the single larger motor with two smaller (yet sufficiently strong) stepper motors placed inside the first and the second panels solved these two problems – See Figures 35, 36 and 37. With two motors installed within each panel, it is now possible to activate each of them independently. Also, the level of tension placed on the cables was reduced considerably.

Figure 35 – Initial conception using a single motor to pull the cables.

Figure 36 – Final configuration using two smaller stepmotors

Figure 37 – 4-tube-hinge in detail

In addition to these alterations the corrugated plastic was replaced by a CNC cut alucobond sheet – See Figure 38 and 39. Also, the single ball caster originally installed on each panel's leg – Figure 40 - was replaced by a laser cut translucent acrylic horizontal platform, which rolls on five ball-bearing casters – Figure 41. The partition was thought of as a modular system that allows the assemblage of as many panels as needed to satisfy the space configuration required.

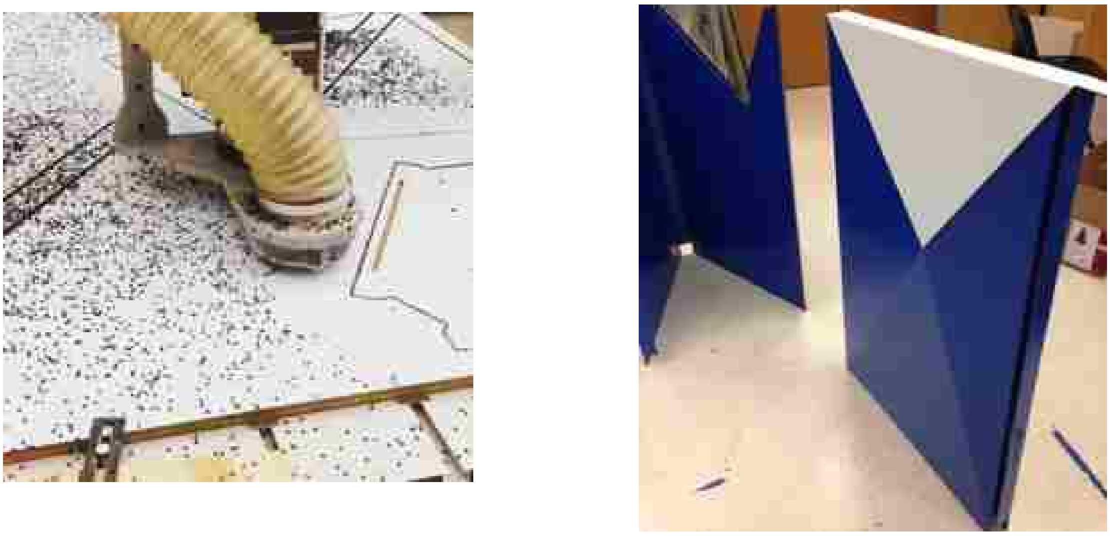


Figure 38 and 39 – CNC for cut and score alucobond sheets

Figure 40 - Single ball caster for each panel's leg

Figure 41 - Horizontal laser cut acrylic platform with five ball casters

Sensing and Control System

The subjects of Human-Machine Interaction and Human-Computer Interaction highlight primary concerns regarding the design of sensing and control of complex system. The exploration of this issue is normally based upon a transdisciplinary body of knowledge, such as Ergonomics, Cognitive Engineering, Robotics, Human Computer Interaction, User Experience Design, and the disciplines of the built environment.

There are several important questions relating this issue such as, (a) how do designers make operator's (i.e. user's) perception of a 'complex work domain' as direct as possible, and (b) how can the operator effectively control a complicated system with several interconnected and interwoven parts in a facile way. These relevant questions were considered when designing the sensing and control system of the chair and the screen.

The functionality of the chair (getting up and lowering) was quite simple to achieve, and thus it could be made as direct as possible. The chair is activated when it senses the presence of a person standing in front of the two ultrasonic distance sensors installed in the front plane of the chair, as shown in the Figure 42.

The chair starts to move from the sitting position to the standing when both sensors detect a fixed object. Once a person accommodates himself or herself on the chair, a switch button (located at the chair's armrest) must be pressed so that the chair moves back to the sitting position.

Figure 42 - Chair's ultrasonic sensors

Once seated, the person is able to control the partition and the table (designed and fabricated by other students) using a control device embedded in the chair's armrest.

As highlighted above, the perception of the operator is an important issue for controlling complex systems. The operator manipulates the screen and the table using only one control device, so there is the concern of which of the two artifacts is 'on' to be activated. Grappling with these issues, HCI and HMI designers need to facilitate the operator's perception and control of a complex system. As highlighted above, one of the concerns regards the misunderstanding of information. One does not want to activate the table by mistake, when the intention was to activate the screen. In this respect, it is of primary importance to design displays that provide clear, well distinguished, and easily accessible information. The same applies to control. A good natural mapping reduces the operators' necessity to learn how to operate the system, and consequently, reduces errors and time for action. The interface (i.e. display and control) will function as a 'window' for human's perception of the system.

The approach I undertook was to divide the controls and display (i.e. blinking LEDs) in two basic categories, as depicted in Figure 43. In the left armrest, the switch and the two sets of led array are the high order types of control. They select and indicate, respectively, which artifact (i.e. partition or table) will be manipulated. The switch positioned forward gives the user the control of the partition. Likewise, the switch pointing backward gives control of the table. The first group of LEDs shows the user which artifact is selected – blue indicating the partition, and green indicating the table. Once the desired object has been selected, the user is able to manipulate it using the Leap Motion sensor installed on the right armrest.

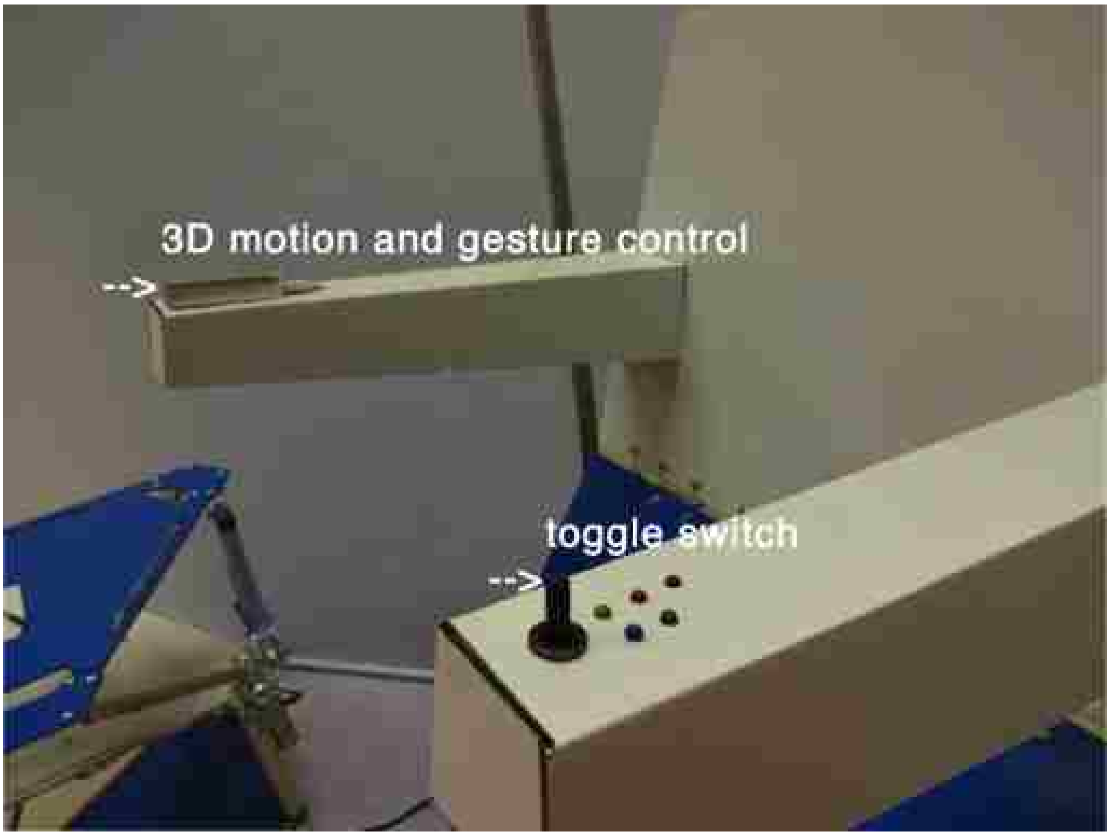


Figure 43 – Controls on the chair's armrest

The control system of the partition is not as simple as the chair's. As described above, the partition is a modular system composed of three panels connected in sequence by hinge-tubes. As Vincente & Rasmussen [33] explain, complex systems like this have several interconnected degrees of freedom that make it challenging for operators to manipulate. It is important to consider that the manipulation of the artifact is intermediated by the control system, that is, there is not direct physical interaction between the operator and the artifact. In this regard, there is the question of how can the operator manipulate the various interconnected parts of the artifact through the control system in such a way that he achieves the desired physical configuration?

My first idea to solve this issue considered the conception of synergy, that is, a linkage between the degree of freedom (i.e. tube-hinge) that would potentially simplify the control. The steering wheel control system is a well know example of this approach – the two steering arms attached to each of the front wheels are connected to the steering wheel, reducing degree of freedom and permitting easier control.

However, this approach was discarded because it would be extremely complicated to design a mechanical system with 'flexible' synergies. The idea was to have each panel capable to rotate independently in order to achieve a greater number of physical configurations. Therefore, too many constraints between the panels would over-limit their degree of freedom and preclude some physical configurations.

I opted for another approach that would rely more on computing and distributed actuation. As described before, this idea considered the installation of two small stepper motors, one at the fist panel and another at the second one, controlling the first and the second tube-hinge, respectively. The Leap Motion sensor would 'link' the degree of freedom and 'unify' the control of the system. When controlling the partition, the leap sensor tracks the position (x, y, z coordinate) of the user's hand. The hand motion drives the locomotion of the artifact – the partition will follow the direction the hand is moving. The position of the hand along the leap sensor will discriminate which panels will be activated – see Figure 44.

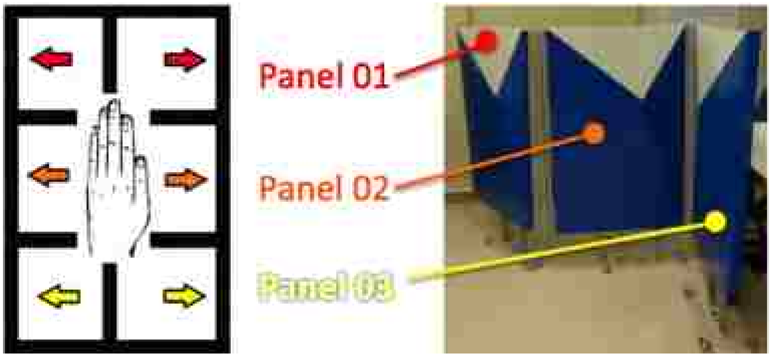


Figure 44 - Control of the partition's panels

Evaluation

After the fabrication of the two prototypes, I evaluated the system with a volunteer elder subject – see Figures 45 and 46. In his first contact, the volunteer did not assume that the chair would start doing 'something' when he approached it. Also, once the user positioned himself on the raised chair, there was an expectation that the chair would start lowering automatically. Clearly, this behavior was due to the volunteer's lack of acquaintance with the chair. I believe that this would be overcome once the user becomes accustomed with the task and familiar with the chair's functionality. This hypothesis was confirmed when he demonstrated a more natural and relaxed behavior in subsequent interactions with the chair.

Figures 45 and 46 - Usability test

Nevertheless, it is important to clarify that these two significant observations indicate that the design did not make clear enough the affordances of the artifact. According to Norman [34] the design of objects and the built environment needs to consider aspects of affordances and 'signifiers' (i.e. signs that informs affordances). It is important to design affordances for humans' capabilities. That is, in order to better support people's activities, designers need to consider the users' capabilities of action. In designing these artifacts, affordances need to be made as clear as possible. These considerations indicate that the next prototype would need to make clearer the presence of the ultrasonic sensors.

It would be interesting to have LEDs around the sensors indicating its presence; as the users approach them, the LEDs could become stronger, suggesting the direction of the 'start'. Another possibility would be having the chair already raised, waiting for the user. Also, adding extra sensors that would inform the user is 'ready' could easily fulfill the expectation of automatic lowering. For this idea, there should be considered some computation and/or loop revision in order to make sure the chair starts lowering at the 'right' time.

Another important observation regards the chair speed of lowering and rising, which was said to be 'too slow'. The user demonstrated impatience with the time the chair took to complete the task. The simple substitution of the current linear actuators by faster ones can solve this issue. On the other hand, faster linear actuators may raise concerns regarding the security of the user. It seems interesting to provide the user the capability to decide the ideal speed of the chair. However, this idea would require the implementation of additional control, and consequently this would result in the increase of the already complex interface.

With respect to the screen, the volunteer liked the concept of creating a more intimate space by drawing the screen closer. It is critical, however, to consider an important fact. The user (i.e. operator) does not have complete overview of the artifact and its surroundings, and consequently, the screen could eventually hit something or someone when the operator activates it. If this study would be continued, the next version of the screen would need to consider this issue. A tempting solution would consider the implementation of a perceptual system. For this one, it would be necessary to install presence sensors on the screen and an additional display (somewhere on the chair), so that the operator could extend his perception beyond the current status.

The volunteer expressed contentment when he was informed that the screen could potentially give support to TV, sound system and other elements that are commonly installed on conventional walls. This idea would require additional study, though, as the installation of such equipment would create potential stability and loadbearing concerns.

The volunteer also suggested the implementation of a fall detection system within the screen. This suggestion is quite proper for the target audience, since falling is common among elder people.

Regarding the screen interface, the volunteer found it difficult to control. First, he had initial difficulties positioning his hand at the correct distance above the Leap. Also, the extra complexity of the user interface for the screen made (minor) training necessary. These feedbacks shows that the user could not easily identify the Leap capability of action, that is, it was not clearly implied a direct association between the hand manipulation of Leap and the reaction of panels. Also, these indicate that the Leap was not ideal for the control of the screen and the table.

A simple and tempting solution for this problem would consist of replacing the Leap with two levers, one for each of the two tube-hinges. The operator would turn each lever right and left to move the corresponding panel. Nevertheless, this simplistic solution does not seem a proper one because it would just substitute a complicated system by another. Besides, the use of levers would not contemplate the problematic of combining various degrees of freedom in only one control device.

Another important implication is that the levers would not be appropriate for controlling the table. This artifact moves right and left, and up and down; therefore, the ideal would be having one lever in horizontal position for right/left and the other one in vertical for up/down. However, this configuration is not optimal for controlling the screen since it would require both levers to be positioned horizontally. As explained above, a good natural mapping reduces learning and consequently errors and time. Certainly, further investigation is highly necessary for the design of the control system with a better stimulus-response compatibility.

Also regarding the interface design, there is a compelling idea of substituting the LEDs installed on the left armrest of the chair by LEDs installed on the screen and on the chair. This proposal seems more natural and easier to understand – the active artifact would be the one with the LEDs 'on'. For the screen, for instance, LEDs would indicate which panels is being activated, and potentially, in what degree. This idea can also reduce the information on the armrest, which seems quite proper since the user could eventually block the visualization of the LEDs with his arm.

Despite some difficulties with the control system, the volunteer welcomed the idea of controlling another artifact (i.e. screen and the table) through the Leap installed in the chair. The volunteer also liked the idea of controlling other elements such as lights, air conditioner, windows and blinds. Once again, this would possibly increase the complexity of control interface.

Conclusion

This project investigated unexplored opportunities in respect to reconfigurable cyber-physical environments in situ to attend to the needs of a specific age group. Thanks to the new advances in medicine, nutrition, among others, people have been living longer and consequently the aged population is increasing. The necessities of elder people have been discussed and a design response proposed. This response considered means of robotics and other digital technologies, and provided a deeper understanding of how people may perceive and interact with intelligent artifacts in our increasingly digital-robotic society.

Lastly, and in broad terms, this research intends to further advance comprehension of robotically mediated human-environmental relationship. HCI design-focused researchers are examining human computer interaction "in the wild." Some have developed electronic devices to observe, supervise and record seniors' health condition as a means assistant caregivers [35]; others provide invaluable insights on how to perceive and sense people in the environment to better respond to users' needs [36], and still others (like me) are striving to create networked and distributed furnishings to actively support aging in place [31].

A remarkable tendency in these efforts, no matter the means, is that the interaction of people and the built environment has been mediated by intelligent and responsive technology, that add a new facet to the long human-environmental relationship. I believe that the design process of networked furnishings to support aging in place, and the information collected and presented from the evaluation test adds significant contribution to the developing research area of architectural robotics and responsive environments.

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