Advancing Smart and Adaptive Living Spaces Through Design and Development of Reconfigurable Multifunctional Robot Rooms

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Plain Language Abstract

Rapid population growth is driving land scarcity, shrinking home sizes and increased housing costs. Additionally, with an increase in time spent at home living spaces must evolve to provide additional functionality to satisfy modern human needs and lifestyle. With the rapid growth in the field, robotics is evolving to further explore human robot interaction in everyday life. In this work, we explore the concept of adaptive living spaces that are capable of transforming themselves physically in real time through the design of a new and novel category of robots called 'Robot Rooms'. We successfully developed, tested and demonstrated a full scale 'slice' of a Robot Room as a proof of concept, in an effort to re-imagine traditional dwellings.

Abstract

This work explores and introduces prototype hardware for a new category of robots: 'Robot Rooms', in an effort to refine the concept of traditional smart spaces and human-robot interaction. Unlike traditional robots that tend to be compact and exist within a space, this new category of robots is designed to be expansive: they do not exist within a space but rather shape space around them. We present several design concepts for potential robotic elements of a Robot Room. We then develop and demonstrate, at full scale, a new and novel concept: a 'slice' of a Robot Room. This slice changes between an open space and various configurations identified as important to human activities in the home. It does so by creating chairs, a table, a bed, and a shelf, as desired by a human user. Testing of the prototype establishes the feasibility of the proposed Robot Room slice concept, and validates the ability to engineer it within prespecified specifications.

Dedication

This work in it's entirety is dedicated to my sister, Preethi, the only person who truly believed in me no matter the circumstance. Your unwavering faith and support have shaped my journey, and I would not be here today without you. Words cannot fully express my gratitude, thank you for everything.

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Next, I would like to thank David Moline form the Electrical Engineering department and Robbie Williams and Austin Breazeale form the Machine shop at the Engineering Innovation building for their assistance in helping me bring this project to life.

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Chapter 1

Introduction

Traditional robot structures include manipulator arms, mobile robots, bio-inspired robots, etc. Robotics research is, however, constantly evolving and expanding to include new categories of robots and new kinds of human-robot interaction. One new category of robots, "inhabitable robots," is emerging and redefining the concepts of "smart spaces," "intelligent environments," and "human-robot interaction." Unlike traditional robots, inhabitable robots are not compact or linear in form. They do not exist within a space but rather create the space around themselves, creating a new form of human-robot interaction whereby people are enveloped by the robot (Fig. 1.1). As such, inhabitable robots offers both a unique set of technical challenges and design interaction opportunities to understand how people can live with and within this new category of robots. As we increasingly expect robots to become a part of our everyday lives, an inhabitable robot represents a transformative advancement in human-centered robotics.

The concept of inhabitable robots has been around for some decades. Architects such as Pask [2], Negroponte [3], Allen [4] and Mitchell [5] hinted at adaptive living spaces from the 1960s to the 90s, but the concepts explored did not extend to full-scale prototypes.

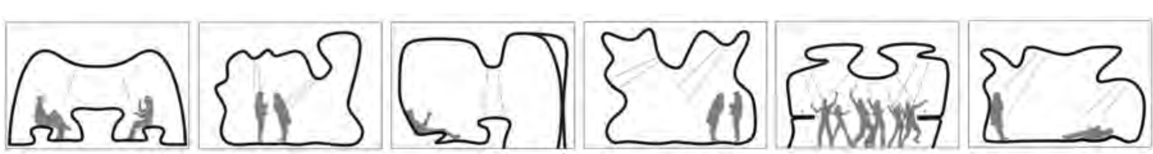


Figure 1.1: In concept, a room that physically transforms into other places, for practical ends (dining/office) or "elsewhere."[1]

Negroponte [3] explored the concept of intelligent environments and responsive architecture by investigating how technology can be integrated into architecture to create living spaces that actively respond to their occupants. Negroponte discussed the importance of creating intelligent environments that respond to user needs without requiring manual manipulation, the use of computational systems to enable such adaptive behaviors there by making such spaces personalized to the individual occupants' preference and needs. He also explored the potential for integrating technologies such as the "you-sensor" which can potentially enable seamless interaction between the living space and it's user, as well as the philosophical conundrum of balancing autonomy and control in such environments so as to create spaces that enhance and support human experience rather than constrain it. The insights and arguments made in Negroponte's manuscript supported the idea of developing inhabitable robots as innovative adaptive living spaces that are capable of dynamically adapting themselves to aid their inhabitants and meet the needs of a modern lifestyle.

Recapping this lineage in his book, *e-topia* [5], Mitchell offered how intelligent environments have the potential to reshape urban life. He conceptualized the future of urban architecture as "robots for living in" where buildings and homes are responsive and intelligent. In this vision, the physical environment would anticipate the occupants' needs and behaviors and would adapt accordingly, providing a seamless integration of technology and architecture.

In 'Three Robot-Rooms/The AWE Project' [6], Green et al. highlight the need for adaptive and intelligent environments to aid the modern lifestyle which includes flexible work schedules, remote work, etc. Motivating the need for dynamic and adaptable work environments, the authors coined the term 'Animated Work Environments' (AWE) for such spaces. The core feature of the AWE concept is the use of programmable and animated architecture capable of morphing to support an array of user needs, providing a strong foundation for the discussion and potential expansion of this concept into the development adaptable living spaces that can transform between various configurations to support diverse human activity within an urban dwelling. The authors highlight the importance of bridging the gap between architectural design and information technology to create intelligent work environments. The idea of inhabitable robotics or 'Robot Rooms' similarly aims to merge smart robotics technology with physical architecture to provide a powerful vision for the future where built living environments act as intelligent adaptive entities, transforming traditional static living spaces into adaptable, dynamic and multifunctional living environments to enhance quality of life.

Intelligent environments however are not limited to physically transforming spaces, they also have been defined to include environments that are capable of sensing, perceiving and then responding to human behavior using tools such as computer vision, speech recognition and sensor networks. These smart environments utilize cameras, microphones and various sensors to track user activity, interpret mood by tracking facial expressions thereby enabling human computer interaction. In this vein, Pentland envisioned environments or 'smart rooms' that can identify individuals and track their movements in an effort to understand their intentions [7]. These smart environments are envisioned to be omnipresent but unobtrusive, providing assistance only when required. These spaces are designed to rely on gestures, speech and facial recognition for interaction. The application of such rooms include but are not limited to work environments and homes for tasks such as adjusting lighting, temperature control and providing notifications based on the occupant's mood and activity. Such smart rooms are an example of early efforts in creating intelligent environments that respond to users. While these rooms primarily focus on the digital recognition and response, adding a physical reconfiguration layer in tandem allowing rooms to morph structurally to create dynamic and responsive living environments provides a novel and alluring challenge.

In the 2010s architect Gary Chang transformed a 344-square foot apartment in Hong Kong into a versatile living space known as 'Domestic Transformer' [8]. He used a system of sliding walls and foldable furniture which allowed the space constrained apartment to morph into 24 distinct configurations, which included a living room, a kitchen, bedroom, etc. The adaptive nature of the apartment lends itself to potentially address challenges of rising urban density due to population growth by maximizing functionality within a limited floor plan. While all the transformations are manually achieved, a potential robotic version of such a living environment motivates the design and development of adaptive and inhabitable robots that can transform confined spaces into multi-functional areas for optimizing space and improving quality of life in densely packed urban cities.

The concept of Robot Rooms: environments that adapt dynamically to human behavior, integrates diverse technologies, including sensing systems, morphable surfaces, furniture, lighting and climate control, decor, and large embedded displays to create adaptable environments that enhance human interaction and utility. In this chapter, we identify the fundamental components that can define Robot Rooms, review these components as developed in research and practice across multiple disciplines, and propose a cohesive framework for understanding and advancing Robot Rooms as a new category of robotics.

Figure 1.2: A wire-frame diagram annotated with key envisioned components of a Robot Room.

Figure 1.2 is a wire-frame diagram annotated with key envisioned components of a Robot Room. Each component is tagged with the disciplines contributing to its research and development, including engineering, Human Computer Interaction (HCI), architecture, and the arts. The components of a Robot Room will likely ultimately include the following:

- Morphable surfaces: Dynamic physical transformations and morphing of surfaces.
- Furniture and devices: Robotic furniture and multifunctional systems.
- Climate and lighting control: Adaptive environmental regulation.
- Decor and embedded displays: Aesthetic elements integrated with functionality.

1.1 Literature Review of Components

This section reviews the state of the art in the above identified components of Robot Rooms and their interdisciplinary development.

1.1.1 Morphable Surfaces

A principal challenge in realizing inhabitable living environments as truly adaptable living spaces is the ability to reconfigure physical environments in response to user needs and inputs. Living spaces are traditionally comprised of flat, rigid and static structures such as walls, floors, tables and ceilings. The ability to change the configuration of, or 'morph', these rigid surfaces helps address the challenge of creating Robot Rooms by enabling the real time transformation of these fundamental architectural elements. Such morphability helps introduce flexibility by allowing the spaces to change function in real time, a feature fundamental to 'inhabitable robots' where the environment must actively transform based on the occupant's needs rather than remaining as a passive backdrop. As such, morphing robotic surfaces represent a critical step toward the development of Robot Rooms. They also present a novel concept in robotics, where prior enabling work involves various actuation techniques such as embedded pneumatic muscles [9], thermal actuation [10], and electro-hydraulic actuation [11] among others. This subsection reviews these advancements in the context of the development of morphable surfaces for potential use in intelligent living spaces. A detailed compilation of the major developments in the research of morphable robotic surfaces is presented in a review conducted by Yang et al. [12].

Traditionally, robots such as robot arms are thought of as compact and linear with fixed joints and rigid links. However, recently researchers are exploring soft robots that are flexible and can more smoothly adapt their form, paving the way for the next generation of advanced robotic systems [13],[14].

In 2019, Digumarti et.al. [14] explored a novel bio-inspired approach to morphable surfaces where in the authors derived inspiration from the Euglenoid pellicle, a naturally occurring structure that enables unicellular micro-organisms to alter their shape. This research introduced a reconfigurable surface composed of polymeric strips that slide against each other, which can in turn enable a soft robotic system to undergo large-scale deformations.

Recent advancements in continuum robot-based surfaces have demonstrated their potential in enabling shape reconfiguration, and in turn their potential for seamless spatial adaptations. Sirohi et al. introduced the 'Space Agent' (Fig.1.3), a tendon driven robot surface capable of adaptively shaping and reconfiguring physical environments [15]. The space agent is a soft, tendon-driven morphable surface deigned to dynamically transform room layouts, work spaces, etc. The authors explore five unique spatial configurations illustrating the robot's ability to support human activity in spaces such as offices, healthcare settings, and autonomous vehicles.

Investigations by Tan et al. [16] demonstrated a novel continuum based robotic surface comprised of woven McKibben pneumatic muscles that is capable of dynamically reshaping environments. Through pneumatic actuation enabled by the McKibben muscles these soft, actuator-driven surfaces were designed to seamlessly transform open spaces into intimate enclosures. They are designed to be scalable, making them ideal for deployment in micro-apartments, office spaces and smart interiors offering an alternative to traditional room and space divisions. Figure 1.4 depicts the use

Figure 1.3: Space Agent: A space-making continuum robotic surface. [15]

of the robot for space partition in a hotel lobby. The robotic surfaces are mounted on the ceiling and remain slightly curved or flat when unoccupied and unactuated. When people gather beneath them, these petal-like structures descend and morph into enclosing shapes to create a more intimate and private space while still offering flexibility such as twisting to allow an individual to step out, demonstrating how robotic surfaces can actively participate in dynamically reshaping environments, and thereby augmenting human activity.

Continuing with the theme of pneumatic actuators, Bhat et al. [17] introduce novel reconfigurable soft pneumatic actuators (SPAs). The authors were able to achieve 360°of bending and over 540°of twisting surpassing many existing designs. This novel design approach provides the user with the ability to substitute the fabric skins of the SPAs as needed to achieve unique deformations without necessitating a complete re-imagination of the actuator's fundamental design.

Chen et al. [18] present a soft robotic surface capable of actively deforming and morphing. The surface itself was designed using hyper-elastic silicone material embedded with bendable

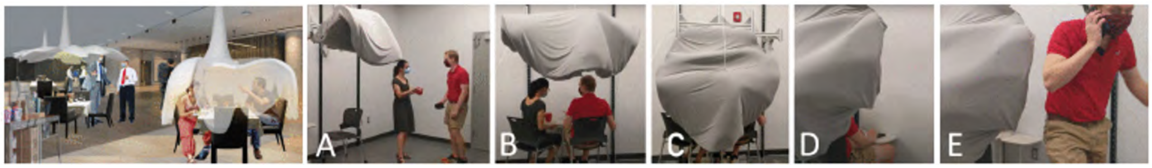


Figure 1.4: Left: A rendering of the robot surfaces elevated and curved downward when people are not seated and seated respectively in the open-plan hotel lobby design case. Right:The full-scale prototype: Two people meet (A) and seat themselves (B), at which point the surface descends and curves (C), "Fully Actuated." After some time, a member of the party needs to excuse himself for a phone call; the surface "Opens to the Right" (D to E). [16]

actuators which are driven by pneumatics.

In a novel approach Bai et al. [19] present a electromagnetically actuated reprogrammable meta surface capable of morphing into three distinct three dimensional shapes. The overall system comprises of a flexible conductive mesh embedded with serpentine beams. The beams are controlled by Lorentz forces which are programmable, these forces being generated by applying electrical current in a magnetic field. Unlike other morphing surfaces, this particular design supports self-adaptive transformations in real time which allows the system to dynamically reshape in response to external conditions. This is enabled via stereo-imaging feedback and optimization algorithms.

The exploration of morphable surfaces has laid a strong foundation for their potential in reconfigurable spaces. These developments directly align with the vision of Robot Rooms and intelligent living spaces where surfaces are capable of actively reshaping themselves in response to user needs. As the field progresses, the research and development of such morphable robotic surfaces highlights a viable path toward scalable morphable surfaces for use in intelligent environments, opening a pathway for a transition from static interiors to more active and shape-shifting environments.

1.1.2 Furniture and Devices

With a growing interest in modular and compact multifunctional living spaces, robotic furniture has emerged as a promising solution to maximize adaptability and spatial optimization in such environments [20] [21]. This field combines modular actuation, automation and intelligent control, and unlike traditional furniture which are often thought of as static, robotic furniture have the capability to dynamically reshape and reconfigure to accommodate user needs. This class of robots facilitate unique shape transformations by leveraging soft robotics, real-time sensing and motorized mechanisms. This in turn is creating a novel framework for interactive, technology-driven human-centered interior design. Robotic furniture are a critical component of the overarching Robot Rooms concept, as a key intersection between robotics engineering and architecture. This subsection will review the advancements in such robotic furniture systems.

Multifunctional furniture have emerged as a promising solution to tackling space constraints in living environments, attracting traction among both designers and consumers owing to their multi-functionality, innovative design and small footprint [22]. Space-saving furniture such as the smart furniture line by Ikea [23], Expand furniture's product line [24], Candra [25] and Dror [26] are increasingly becoming more prevalent. While these examples are not robotic in the traditional sense, they actively contribute to the concept of adaptive living spaces, specifically being space-saving and establishing a foundation for robotic adaptation in the future [27].

Ori living and Bumblebee are industry leaders in physically transforming living spaces and robotic furniture. Ori living's product range, which emerged from MIT media lab's CityHome project, includes a ceiling mounted bed (Cloud bed) as well as the 'Pocket office' and 'Pocket Studio' collection which are smart walls integrated with an office table or and integrated bed. In addition to the smart walls feature, both Ori living and Bumblebee (Fig. 1.5) offer floor and ceiling mounted furniture. The primary objective of these companies and their products is to make use of active, multi-functional furniture to get more out of traditional living spaces by actively changing the the layout of the space in real time [27].

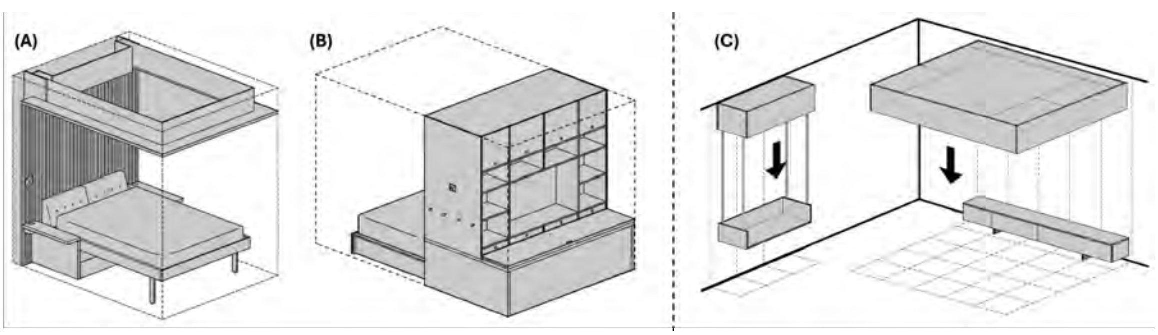


Figure 1.5: Left: (A) ORI cloud bed, (B) ORI pocket studio; Right: (C) Bumblebee bed and table. [27]

Advancements in modular robotics have facilitated the design concept of modular, self-reconfigurable adaptive furniture capable of adjusting based on user demands and spatial constraints. In 2009, Sporowitz et al. first introduced 'Roombots', a novel modular robotic system that is comprised of a number of robotic modules capable of autonomous locomotion and real-time furniture reconfiguration through self assembly. The modules are engineered to operate with three degrees of freedom and are capable of forming various furniture configurations such as chairs, tables and stools, enabling active, multifunctional living spaces. Figure 1.6 (A) illustrates the initial concept sketch of the 'Roombot' while Figure 1.6 (B) depicts snapshots of the chair formation sequence [28] [29].

The advancement of robotic furniture technology is not limited to reconfigurable furniture. Recent research has explored user-centered, self-organizing furniture systems. Specifically, Fallatah et al. introduce 'ChairBots', a novel robotic chair system capable of autonomously repositioning itself based on user direction. The overall system is designed to allow multiple robotic chairs to move in unison to re-arrange the layout out the room to save time, manual labor and optimize space based on various use cases. The authors envision this system being deployed in places such as classrooms, offices spaces, and event spaces where frequent furniture reorganization is typically prevalent [30].

Building on a similar concept, Preteneder et al., introduce 'Foxels', a modular and interactive smart furniture system with the aim of redefining user interaction and engagement within the context of adaptive environments. Unlike traditional furniture which tend to be static, Foxels are modular building blocks that can be snapped together to form a number of functional furniture pieces such as tables, chairs and storage units through gesture-based interaction, enabling users to dynamically reconfigure the furniture layout in a room [31].

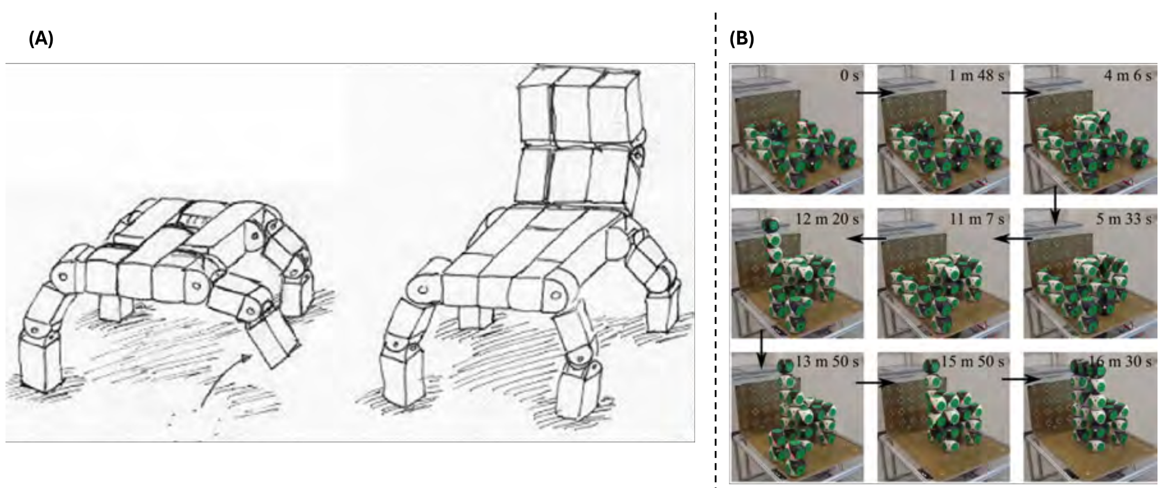


Figure 1.6: Left: (A) Illustrates the initial concept sketch of the 'Roombot'; Right: (B) Sequential images depicting the chair formation process [28] [29].

The recent advancements in the research and development of multifunctional robotic furniture reflects a fundamental shift in the design of living spaces, evolving towards dynamic, adaptive and reconfigurable living spaces capable of responding to real-time user needs. Advancements in self-reconfigurable furniture systems and modular robotics have validated the viability of intelligent furniture enhancing the functionality and efficiency of traditional living spaces. As the research progresses, advancements in the field will drive robotic furniture toward a future where adaptive interiors will be capable of seamlessly and intuitively adapting themselves to maximize space, and to improve comfort and flexibility.

1.1.3 Climate and Lighting Control

The idea of adaptive living environments is not limited to physical transformation within living spaces, it extends to effective climate and lighting control, both of which impact the inhabitant's comfort and well being. Traditionally, interior lighting and temperature control systems are not designed to adapt in real time based on user needs, however, recent advancements in the adaptive lighting systems and intelligent climate control technology leverage sensor networks to create responsive and self regulating living spaces that can actively adjust the lighting, temperature based on user preferences. This subsection reviews the innovations in such technology, examining how sensor driven automation can contribute to adaptive living spaces capable of responding to their occupant's needs.

With people spending increasingly more time indoors, there has been an emphasis on the development of smart lighting technologies in indoor spaces. Zou et al. introduce a novel inhabitant driven lighting control system, 'WinLight'. 'WinLight' is capable of autonomously controlling and adjusting the luminosity of lamps within an enclosed space based on the location of an occupant by leveraging the WiFi network in the space. The occupants also have the option of manually adjusting the brightness through a mobile application offering more control to the user [32].

In a similar effort, Saranya et al. proposed an innovative universal smart lighting system capable of adapting to various environments and lighting needs. Analogous to 'WinLight' the device is WiFi compatible, and can be controlled via a smart phone application. The system is sensor driven and is capable of dynamically adjusting the lighting by detecting occupants within the space in an effort to create a natural and comfortable environment [33].

The rapid growth of wireless technology and internet of things (IoT), has created promising avenues to explore adaptable lighting control in living spaces. There have been a number of investigations into leveraging these technologies to not only dynamically control lighting but also to develop sustainable and energy efficient lighting systems that contribute to smart living spaces that can adapt based on their inhabitants [34, 35, 36, 37].

With Human Robot Interaction (HRI) at the heart of the work, Schuttler et al. present a novel gesture control based approach to control smart lighting systems. The authors make use of an 8x8 infrared sensor array embedded with machine learning (ML) models for accurate and contactless lighting control in an effort to improve user experience and paving the way for innovative design strategies for smart living environments [38].

Authors Sana and Rana investigate the ways in which sensor powered responsiveness, automation through IoT and artificial intelligence (AI) can contribute to enhancing efficiency in living environments. This research places an emphasis on dynamic climate control and lighting and illustrates the feasibility of incorporating such sensing technology in living environments in a effort to create more flexible and responsive interiors [39].

There have been significant advancements in research involving AI powered control systems and optimized control systems for the development of smart and energy efficient living environments [41, 42, 43, 44, 45, 46]. Dounis and Caraiscos explore and preform a review of multi-agent control systems and their role in the development of self regulating interiors capable of dynamically adjusting to external conditions and user needs [47]. Mehmood et al. offer an expanded perspective of AI and big data in energy-efficient buildings and showcase how data driven modeling has the potential to enhance energy efficiency and comfort in indoor living environments [48]. In 2021, Merabet et al. highlighted the role of predictive algorithms and machine learning (ML) to enhance HVAC efficiency and overall occupant wellness [49]. These reviews highlight the growing significance and potential of sensor and AI driven automation in enhancing and shaping smart, adaptive living spaces. In addition, there are a number of reviews that survey developments in such smart technologies and cover the broader topic of the use of these technologies in smart, energy efficient buildings and living spaces [50, 51, 52]. Vijayan et al. additionally provide a thorough review of smart building automation systems [53].

Kadhim et al. explore adaptive facades as a sustainable solution to improve inhabitant comfort and energy efficiency. Traditionally building facades are static, however, the adaptive facades developed by the authors respond dynamically to environmental stimuli in an effort to optimize temperature, ventilation and lighting [54].

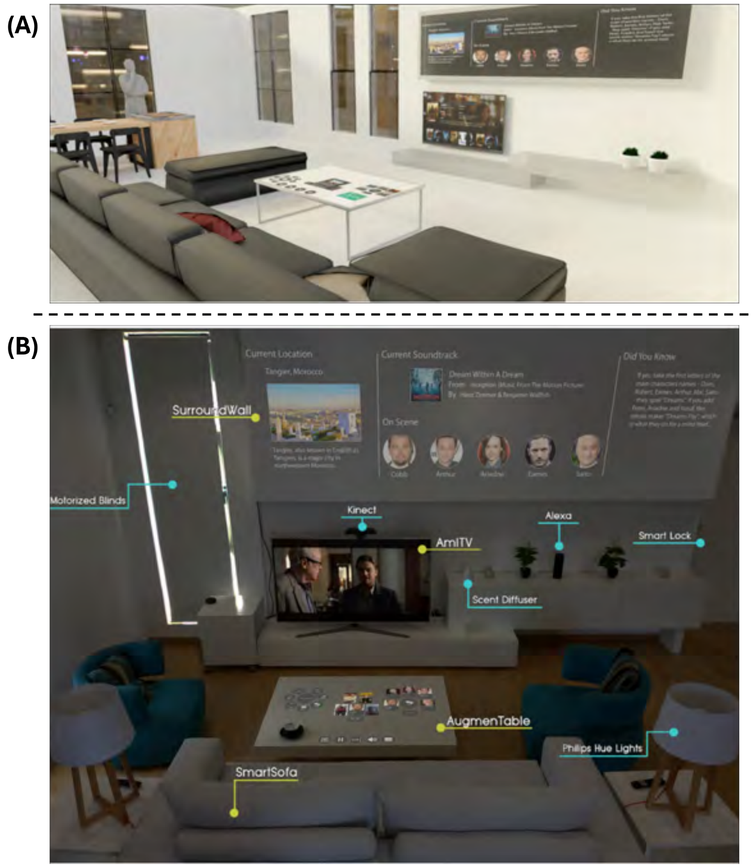


Figure 1.7: Top: (A) Realistic 3D rendering of the 'Intelligent Living Room' developed early in the prototyping phase. Bottom: (B) Hardware realization of the 'Intelligent Living Room' prototype. [40]

As the works referenced in this subsection demonstrate, advancements in AI, IoT based sensors, wireless networks and adaptive facades have helped redefine and facilitate the development of energy efficient, user-centric adaptive living environments capable of real-time adaptation in response to their inhabitants. As these technologies evolve, the design of smart buildings will evolve with them, ensuring that sustainable user-responsive environments will remain at the forefront of modern dwellings.

1.1.4 Ambient Intelligence and Embedded Displays

As evidenced above, there have been advancements in the development of environments that are aware of inhabitants and are capable of intelligently responding and adapting to users (ambient intelligence) [55]. This technology has the potential to influence all environments involving human interaction, including the home [56, 57, 58, 59].

Leonidis et al. explore the role of living rooms within the context of environments with embedded ambient intelligence. In this account, the authors present the design process involved in the hardware and software development of a technologically advanced living room called 'Intelligent Living Room' (Fig.1.7) designed to improve the quality of life of the room's inhabitants. In addition, the authors also present the results of various user based evaluation experiments in an effort to assess the applications and the functionality of the room, along with the overall User Experience (UX) [40].

In an effort to study and understand how projected visualizations can improve, suppress or be seamlessly integrated into the existing physical environment, Jones et al. first introduce 'IllumiRoom'. 'IllumiRoom' is a prototype system that is capable of augmenting the area around a television by making use of projected visualizations as a way of complementing the content on the television to enhance user experience [60].

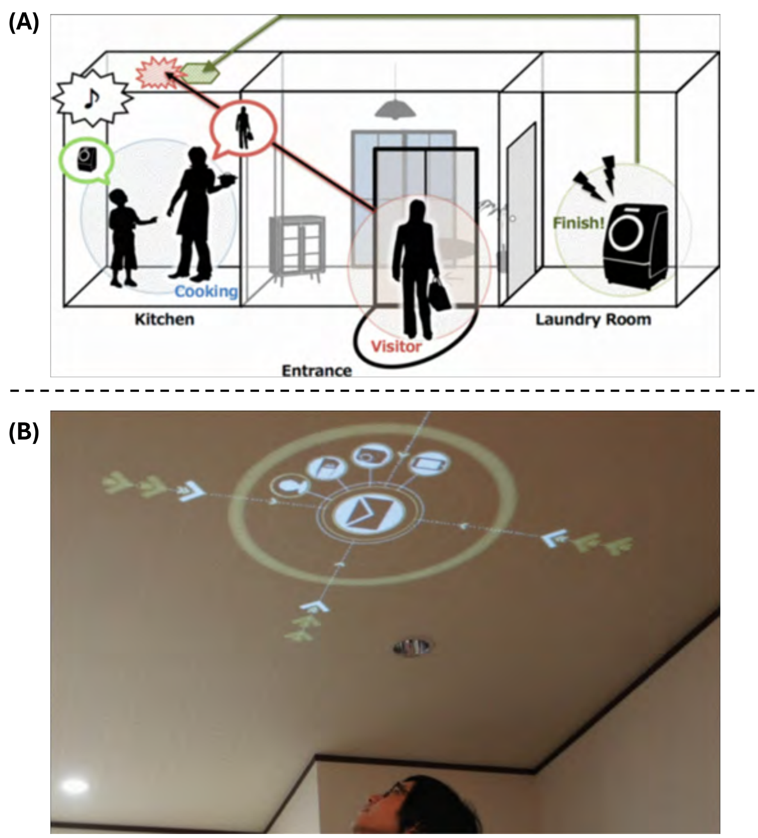


Figure 1.8: Top: (A) Conceptual overview of 'ToDo' ceiling display system in a smart house. Bottom: (B) Prototype realization of a sample 'ToDo' list displayed on the ceiling. [61]

Following ‘IllumiRoom’, in a separate effort, Jones et al. introduce ‘RoomAlive’ a novel proof-of-concept prototype designed to transform living spaces into an immersive and augmented experience. With projector depth cameras at the heart of the system, ‘RoomAlive’ enables an interactive projection capable of projecting content on to a room and dynamically adapting based on user input. Users are able to touch and steer the projected content, seamlessly blending into the physical environment [62].

Sticking to the theme of projector based Ambient intelligence, Xiao et al. developed ‘World-Kit’, a projector based system that was designed to turn ordinary non-active surfaces in everyday living spaces into touch based interactive ones with the wave of a hand. Drawing inspiration from prior works such as ‘Everywhere displays’ [63], ‘LightWidgets’ [64], and ‘Lightspace’ [65], the design of ‘WorkdKit’ is rooted in vision based sensing. The system was designed with the aim of providing instant access to computing services as and when needed, turning everyday living spaces into smart and active spaces [66].

The concept of projector based technology to augment everyday life has mainly yielded smart spaces with interactive tables and walls. However, there has been some exploratory work into using ceiling as a canvas for such interaction [67, 68]. Hiram and Kamakura, by proposing ‘ToDo’ (Fig.1.8), a ceiling based display system designed for a smart living space capable of projecting information such as the inhabitant’s everyday task list as well as notifications from appliances around the house as needed based on the inhabitant’s location within the living space [61].

The research into ambient intelligence and related technology is growing. A number of surveys have examined the progress in this area and are featured within several comprehensive reviews on this subject [69, 70, 71]. Rooted in the area of human computer interaction, the idea of incorporating embedded immersive displays as a fundamental part of smart living environments in an effort to expand and enrich user experience in such spaces is rapidly gaining traction. The integration of ambient intelligence opens the door for living spaces to be intuitive, context aware and physically responsive to inhabitants. As the field evolves, it has the potential to play a decisive role in reshaping the future of living spaces.

1.2 Integrating the Components into a Robot Room

In it's truest form, a 'Robot Room' is not a single innovative entity but rather a collection of core individual components that come together to form truly adaptive living spaces that are capable of adapting both physically and digitally in response to inhabitants. The major individual components listed and reviewed in this chapter include: morphable surfaces, robotic furniture and devices, climate and lighting control systems, and ambient intelligence and embedded displays.

Each individual component plays a distinct role in shaping the environment. Morphable surfaces and robotic furniture in tandem form the flexible architectural backbone. They enable real-time physical reconfiguration, which in turn facilitates spatial reconfiguration in an effort to create infrastructure that is functionally responsive and capable of supporting diverse human activities.

As previously mentioned, the idea of adaptive living spaces is not restricted to physically transforming spaces: climate and lighting control and ambient intelligence are key contributors to environmental intelligence. While smart climate and lighting control contribute to autonomously managing comfort and energy efficiency, ambient intelligence within living spaces allows living spaces to perceive, communicate, react and interact to inhabitants. These two components also potentially help transform the environment into a portal to "other places" in an effort to serve both practical and escapist needs of the inhabitants.

Together, all four major components can converge to cooperate and form a cohesive and interactive ecosystem where the line between inhabitants, physical space and technology blur and enable 'Robot Rooms' to seamlessly adapt and respond to human needs. Robot Rooms represent a new paradigm in smart living spaces, one that is dynamic, personalized and physically reconfigurable.

1.3 Dissertation Preview

In this dissertation, we present a new and novel contribution to physically reconfigurable living spaces. This work explores and presents the physical realization of a new category of robots: 'Robot Rooms', in an effort to refine the concept of traditional smart spaces and human-robot interaction. We have developed and demonstrated, at full scale, a new and novel concept: a 'slice' of a Robot Room. We then subjected the prototype to a series of experiments in an effort to establish the feasibility of the proposed Robot Room slice concept, and validate the ability to engineer it within prespecified specifications. The prototype presented in this work integrates two of the four major components discussed earlier in this chapter, namely, furniture and devices and morphable surfaces. However, incorporating ambient intelligence and lighting & climate control was beyond the scope of the work presented here, offering a valuable avenue for future exploration.

This remainder of this section provides an overview of the contents and contributions of the remaining chapters of this dissertation.

In Chapter 2 we discuss our initial efforts in investigating and creating Robot Rooms. We further discuss how we built on that early work by conceptualizing and realizing a full-scale prototype of a novel physically transforming living space, a “Robot Room slice”. In Chapter 3 we examine the experimental testing and evaluation of the prototype and assess the system’s performance against predefined specifications. In Chapter 4 we wrap up major contributions with conclusions, a discussion on wider applications of the research presented here and suggestions for future work.

Chapter 2

Research Design and Methods

In this chapter, we describe our initial efforts in investigating and creating Robot Rooms, as reported in [1]. We further discuss how we built on that early work by conceptualizing and realizing a full-scale prototype of a novel physically transforming living space, a “Robot Room slice”.

2.1 Realization of Robot Rooms - Early Work

2.1.1 Early Vision and Physical Prototype

In an early vision statement [6], a Robot Room was envisioned as an “articulated, programmable, physical environment embedded with integrated digital technologies.” Two concepts for a Robot Room, drawn again from [6], are: “Concept-1,” defined as “a typical room with. . . an insertion of a series of shape-shifting, ribbon-like components”; and “Concept-2,” defined as “a seamless, three dimensional envelope rather than the collection of components.” Fig. 2.1 illustrates these two concepts in diagrammatic terms: the ‘Components in a room’ concept (“A”); and the ‘Whole room’ concept (“B”), made of three modules: a plane (d), a corner (e) and an angle (f) that together, in multiples, create a seamless room envelope. Fig. 2.1 also offers visualizations of two concepts: “C” being suggestive of the ‘Components in a room’ concept; and “D” being suggestive of the ‘Whole room’ concept. These concepts served as inspiration for our early efforts.

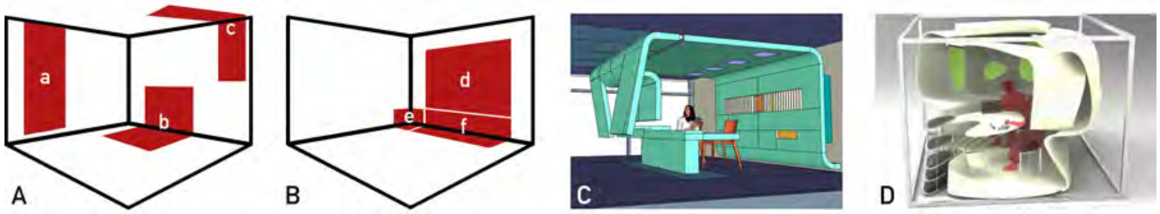


Figure 2.1: Two Robot Room concepts and semblances of what they might look like: (A) the 'Components in a room' concept where (a), (b) and (c) represent three robot-surface components; (B) the 'Whole room' concept, made of three modules: a plane (d), a corner (e) and an angle (f) that together, in numbers, make a room envelope; (C) and (D) are visualizations we made some years ago that, respectively, are suggestive of the 'Components' and 'Whole' room concepts.

2.2 Motivating Use Cases for a Robot Room

We initially envisioned developing the 'Components in a room' concept, as suggested in Fig. 2.1, with robotic elements distributed in some numbers in a room, at floor level, below the ceiling, and perhaps in between and within the space of the room to form a Robot Room. Our initial designs and prototypes (reviewed in the following section) were based on this concept.

We chose the home as the focus for our Robot Room research given that the home, however manifested — house, apartment, co-op, co-housing — is the building typology that accommodates the widest range of human activity: a place for rest, meal preparation, sleeping and socializing, also an office, a school, a playground and a gym. On Earth, as we mass-urbanize, as land in certain regions becomes more prohibitively scarce and expensive, and as we spend more time doing more things at home, our homes, getting smaller, necessitate more physical affordances tuned to our busy lifestyles, on the go, at home.

Complicating the strain on the over-programmed home are two associated trends: mass-urbanization and the shrinking size of urban dwellings. By 2050, two-thirds of the Earth's population is expected to reside in urban areas [72]. Meanwhile, the most populated cities are experiencing unprecedented population growth. To accommodate the growing number of urban dwellers, homes are getting smaller: in New York City, dwellings now average 414 sq. ft. per person, in Paris, 388 sq. ft., and in Hong Kong (where home prices have tripled in a decade) 160 sq. ft. and, for subdivided apartments, a mere 48 sq. ft. [72]. The main room of a small home is an ideal site for a Robot Room that can actively reconfigure itself to serve many functions.

We pose two, core research questions: (1) how can a home be outfitted with a Robot Room that reconfigures into "many forms"; and (2) how are inhabitants of a Robot Room supported and augmented by it, following real-world needs?

To respond to these research questions, we identified real-world needs for a Robot Room by turning to how people living today reported on their problems and opportunities of living in small, relatively confined living spaces as documented in an article from The New York Times appearing in the period during which many of us were under a quarantine mandate due to Covid. This use case addresses the practical need to physically reorganize the interior of the dwelling place to accommodate a myriad of human activities. (A second use case, also motivational but generally outside the scope of the work reported herein, captures the desire to escape the confines of the dwelling space by reorganizing it to evoke "other places" outside its walls.)

Motivating Use Case: A Robot Room Serving Practical Needs

"They Remodeled Before Covid. Here's What They Regret Now," January 14, 2022 [73]. Pre-pandemic, the architects for a loft remodel in New York City allocated one-third of the loft's space to work activity, two-thirds for family life. This allocation worked well at the start of the pandemic "when the grandchildren often visited, using the open living space as a playroom"; but soon, "desperate for more space and quiet, ... the 4-by-7-foot closet in the guest room" became an office entered by ducking under a beam. In this closet-office, "there were days when Mr. Uriu was on the phone trying to salvage his business ..., while Ms. O'Mara was trying to keep the attention of children as she taught art classes over Zoom, separated [from Mr. Uriu] only by Soji screens." This provides a core motivation for a Robot Room, adaptive to changing programs, serving practical needs.

2.3 Initial Prototypes

2.3.1 Prototype 1: Reconfigurable bed/chair

Inspired in part by the above concepts, our initial prototype was a version of the 'Components in a room concept' ("A", Fig. 2.1), specifically, component A(b) which is the floor component in a Robot Room concept. The prototype was a scaled-down simplified concept of a multi-functional chair/Chaise lounge designed to transform itself into either a bed or a table based on user needs.

Fig. 2.2 (A) represents the side view of the prototype in its "Chaise lounge/chair" configuration. Fig. 2.2 (B) represents the same in its bed/table configuration.

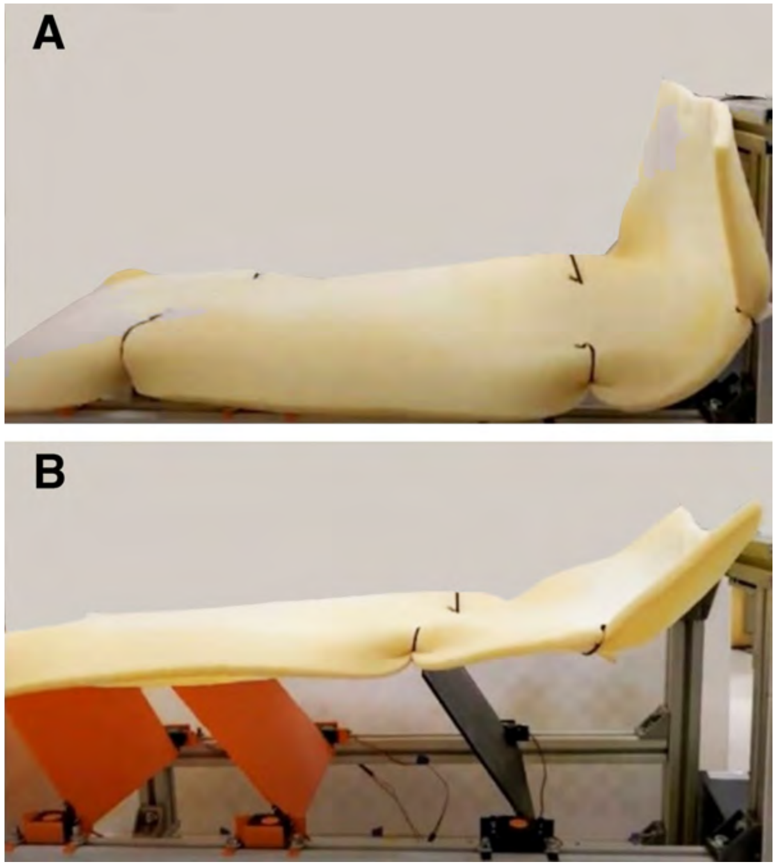


Figure 2.2: Side view of initial prototype and it's two configurations: (A) a chaise lounge for relaxing, and (B) a bed for sleep or rest.

The basic design philosophy was to use surface on surface interaction to create the desired change in shape. This change in shape was achieved by the interaction between a set of three rigid 3D printed flaps (Fig. 2.2 (A) and (B)) which are actuated from 0°(natural chair/Chaise lounge configuration) to 90°(bed/table configuration) sliding across the interior of a piece of foam which forms the surface of prototype 1. Each flap measures approximately 11.85x9x0.2inches and is actuated using a pair of MG995 servo motors. The current configuration (angle) is displayed on an LCD screen. At the heart of the system is an Arduino UNO, which is used to drive and control the motors and all the electronics used in the prototype. The flaps were designed using Solidworks and 3D printed using an Ultimaker S5.

Our early prototype design efforts yielded a number of insights, which include, the need for the robot to be firmly grounded post reconfiguration to ensure stability when under heavy load to support human activity. Embedding the circuity and actuation hardware within the robot is advantageous from both a practical and ergonomics perspective. Finally, minimizing the number of motorized components (i.e. actuators) helps to simplify the complexity associated with control and synchronization.

2.3.2 Prototype 2: A Shape-Adaptive Robot Surface

Developing the concept of surface on surface interaction, we also engineered a novel, robot surface design in which flexible robotic tendrils interact with a compliant surface to achieve different 2D configurations. The tendon-actuated continuum elements enable the surface to lift, lower, and morph into various shapes, highlighting the interaction between tendrils and surface in forming these configurations. We envisioned the system, when scaled up, to be effective in reconfiguring small rooms to support human activities of many kinds.

The core of the robot (Fig. 2.3) consists of a pair of thin tendon-actuated continuum elements, or tendrils, which interact with a soft, flexible surface to form a desired range of shapes. The surface, a 25.4 mm (1 inch) diameter mat made of jute (see Fig. 2.3-bottom) [74], was selected for its balance between compliance and rigidity. Specifically, the surface material was carefully chosen to ensure that it was compliant enough to deform under the forces exerted by the tendrils, yet sufficiently stiff to deform evenly when interacting with the tendrils.

The robot's chassis (see Fig. 2.3-top) features a 3D-printed structure affixed to a wooden base, with the continuum tendrils supported by precision bearings to ensure smooth and stable operation. The overall system architecture can be divided into three distinct mechanical subsystems: tendril rotation system, tendon pulling system, and surface rotation system. Each subsystem introduces independent degrees of freedom, enabling versatile interaction possibilities between the tendrils and the surface, and enhancing the functionality of the robot. The tendril pulling system employs two “DS3218MG” digital servos (20 kg torque), each fitted with a 3D-printed pulley to actuate the continuum elements. The tendril rotating system is powered by a ‘MG995’ continuous servo which drives a pair of timing pulleys via a timing belt on each side of the robot designed to transmit rotational movement.The surface rotating system is comprised of a “MG995” continuous servo, a pair of plastic gears, and the surface itself.

The electrical system of the robot is controlled by an Arduino Mega micro-controller, which is powered by an adjustable 12V/40A power supply. The power supply output is regulated to 6.0 VDC to drive the five servo motors integrated into the system. The servos are controlled through

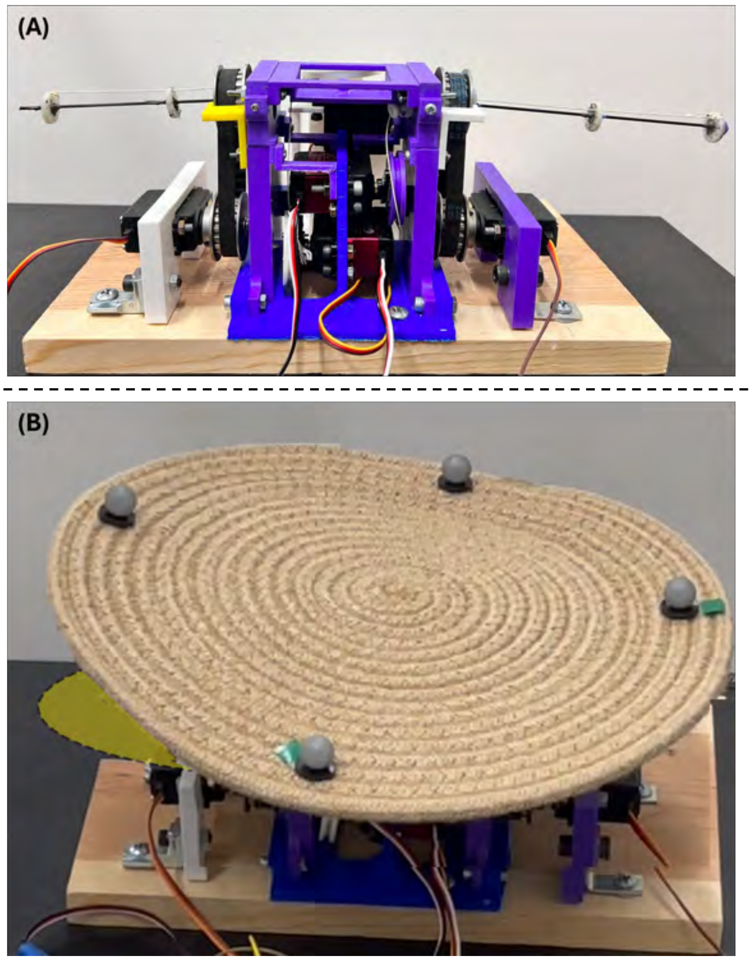


Figure 2.3: Surface Robot: Top (A) Front profile of the robot without the jute surface, showing the exposed tendon-actuated continuum elements (tendrils), the 3D-printed chassis, motors, pulleys, and tendon systems; Bottom (B) Front view of the robot with the 12-inch diameter jute surface in place.

an open-loop control system, enabling either independent or parallel control of each component.

This prototype refined our experience of designing robotic elements suitable for deployment in Robot Rooms, and demonstrated how incorporating tendon-actuated continuum elements can generate complex surface deformations. Our initial plan was to further develop this concept in creating 'Components in a room' robot environments. However, information from research conducted by our research collaborators, summarized in the following section, resulted in a change of emphasis and design methodology.

Figure 2.4: Eight spatial configurations of a 7'-8" three-segment robot surface with a 5'-7" figure.

2.4 Human Centered Design Study

In parallel to the above work, our collaborators in this research at Cornell University identified eight spatial configurations potentially achievable by robot surfaces (scaled to be ergonomically correct) (Fig. 2.4) and seven domestic activities these configurations might support. The human activities are: A) eating dinner with family, B) reading to children, C) watching TV with partner, D) napping, E) taking a video call, F) (no explicit activity), G) conducting an online (Zoom) meeting, and H) working on a computer. They conducted an online survey consisting of 52 questions in an effort to explore the response to the concept of Robot Rooms and their applications. A total of 77 participants, 37 females, 38 males, two non-binary, with a mean age of 29.7 years were recruited across the US, Canada, and EU countries.

The participants were presented with the eight configurations from Fig. 2.4 and the seven activities these configurations supported. The participants were instructed to identify the most suitable activity followed by their next preferred options for each of eight configurations and vice-versa. Configuration H proved to the most versatile from the participant's perspective, while D, E and H were most selected for "Take a nap", "Take a video with friends" and "Do work on a computer", respectively.

In an effort to better understand how well the configurations and activities were matched, any activity-match selected by 35 out of 77 participants were classified as "Suitable" while those that were selected by fewer than 15 participants were classified as "Unsuitable". Configurations F and H were perceived to be suitable for four activities and thus proved to be the most versatile in the eyes of the participants. Additionally, combinations of configuration pairs F-H or D-H yield seven unique activities. The participants associated configurations F and D with activities such as watching TV or taking a nap, activities that are traditionally perceived as "Relaxing", while configuration H was associated with traditionally "productive" activities such as working on a computer or taking a meeting.

From a user point of view, the results of the survey suggest that a “Robot Room” that supports two configurations F-H or D-H is comparable in effectiveness and performs on par with a room that supports eight configurations, and the former reduces the engineering effort needed considerably.

The participants were then presented with a series of GIFs and static images of our prototype 1 and its various configurations as illustrated in Fig. 2.2. They were then asked to select the activities they judged most supported by these configurations and to rank the preferred means for controlling the robots. A significant 81.8% of respondents identified the transformation of the prototype as a transition “from a lounge chair to a bed,” and 80.5% of participants believed in A’s capacity to support activities ranging from watching TV to taking a nap.

Our examination of the survey results yielded a pair of key observations from a design point of view. Users did not want a “Robot Room” that was fully autonomous, they preferred having significant control in the robot’s operation. The second observation that was drawn was that the users felt that they did not need a complete “Robot Room” that offered an extensive number of discrete robots to support their activities; users felt that part of a room that offered fewer (but key) configurations was just as effective. These observations influenced our ultimate conceptualization and full-scale prototype design of a physically transforming living space that was closer to the ‘Whole room’ concept in Fig. 2.1.

The subsequent sections of this chapter will describe our conceptual framework for developing a novel ‘Robot Room slice’ and the design methodology we employed in realizing a full-scale prototype of a physically transforming living space.

2.5 Conceptualizing a Physically Transforming Living Space

Following our initial work discussed in the previous section, the next phase of our research involved conceptualizing what a physically transforming living space (“Robot Room”) could look like and how that design would function at full scale.

Based on the feedback from the survey summarized in the previous section, and looking at what furniture/furniture configurations are typically present in living spaces, we came to the conclusion that every home has and will always have tables, chairs, beds and shelves, and that these are traditionally are the most ubiquitous furniture making them the natural choice. Once we narrowed down the furniture configurations we moved on to answering a more challenging question, *How do we design a room that is capable of actively reshaping itself in order to produce these furniture configurations based on inhabitant needs without using up valuable real estate?.*

No matter the the shape or size of the dwelling, floors and walls are the foundational elements of every living space. Taking inspiration from them, we can imagine a living space where these foundational elements are capable of actuating in real time based on user input to transform themselves to form the desired furniture configurations. This gave birth to an "Active Discrete Floors and Walls" concept.

However we quickly realized that building a living space or even a room where all the floors and walls were capable of actuating was unrealistic. Re-imagining the idea, we conceptualized a smaller 'slice' through the room capable of performing the same functions, with the big picture being that a number of these individual slices put together could have the potential to form a whole room and in turn a complete dwelling capable of physically transforming. This 'Slice through the room' concept is not only easier to engineer, but also gives the users more flexibility to choose the extent to which the space is robotic. While some users may want only a small portion of their living space to be robotic, some might want a much larger percentage of the space or eventually the whole space to be able to transform, and this 'slice' design concept offers them the flexibility to choose based on their individual preferences. Either way, the core elements identified in the survey reported above should be present (or have the capability of being included) in a room slice. This 'Slice through the room' concept is a novel and foundational concept that enables modular, and scalable robotic living environments.

Once the concept was finalized, our colleagues at Cornell University produced a conceptual rendering of the the 'Active floors and walls' and 'Slice through the room' concepts as illustrated in Fig. 2.5. We then identified a number of design specifications and requirements the final robot system would be required to meet. These included: required configurations the robot should produce; the amount of load each configuration could bear; and maximum time it would take the robot to achieve these configurations. These core specifications are presented in Table 2.1, and the motivation for the specific values is discussed next.

Per the Center for Disease Control (CDC), on average American adult males weigh 199.8 lbs [75]. Adding a safety factor of 50 lbs, we set the desired load bearing capacity of the chairs to be 250 lbs. While load bearing capacities of tables can widely vary based on material and dimensions,

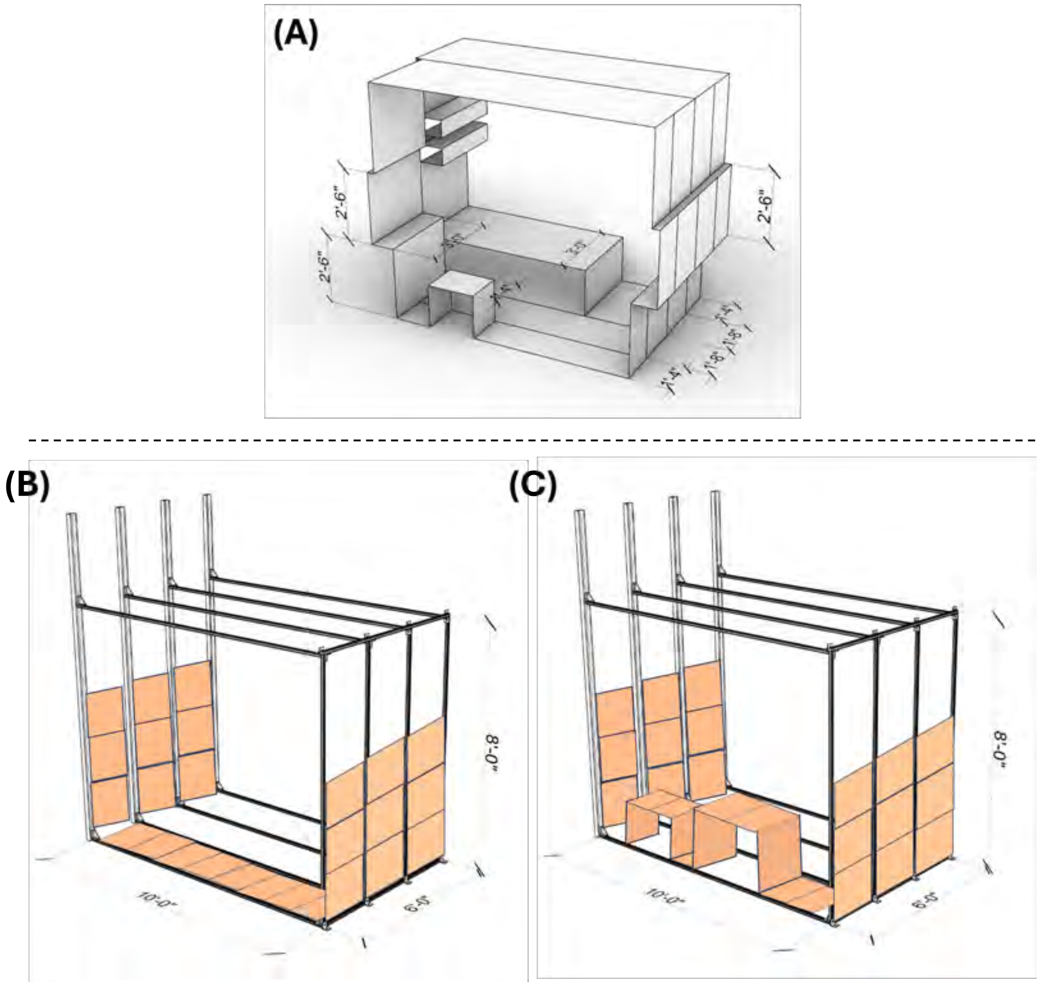


Figure 2.5: Early conceptual rendition of a living space illustrating the 'Active floors and walls' and 'Slice through the room' concepts. Credit: Green research group, Cornell University.

a 36" X 36" national public seating table from WB mason can support 300 lbs of equally distributed weight, [76]. Based on this, we set our target load bearing capacity for the table to be 300 lbs. A report that summarizes ergonomic standards for office chairs recommends a minimum seat height of 14.8 inches [77]. Based on this we set our minimum desired height of the chair to be 15 inches. Since tables vary vastly in design, there is a lack of similar standardized design recommendations for tables. Therefore we set the minimum height requirement for the table to be 50% more than the chair, which was evaluated to be 22.5 inches.

Similarly, due to a lack of standardized metric for the height of a bed frames, we looked at metrics presented by a mattress manufacturer. This information categorized bed frames into 3

Desired Elements	Minimum Height (in)	Minimum Load Bearing Target (lbs)	Maximum Configuration Time (M:s)
Floor	N/A	300	N/A
Table	22.5	300	2:00
Chair	15	250	1:30
Bed	16.5	250	2:00
Shelf	10	20	1:30

Table 2.1: Design Specifications.

categories: low profile, with an average height of 9-13 inches, medium profile, with an average height of 13-15 inches, and high profile of 15 inches or greater [78]. Based on this information we decided on a minimum of 16.5 inches by averaging the lowest profile (9 inches) and the highest profile (15 inches). Similarly to the process for the chair, based on the weight of an average American adult male, and a 50 lbs safety factor, we set the load bearing target for the bed to be 250 lbs.

Based on standards recommended by public christian library and other commercial residential shelf manufacturers such as IKEA and Wayfair [79, 80, 81], on average book shelves are 10-12 inches deep. Using this as a base metric we set our minimum desired shelf depth to be 10 inches. Based on recommendations by online shelving retailers, floating shelves can hold anywhere from 20-100 lbs deepening on the number of anchor points. Since there are not any anchor points in our design, we decided to keep the load on the shelves to a minimum and set the minimum target load bearing capacity for the shelves to be 20 lbs.

Due to the novelty of the design, there is a lack of prior performance standards or references in literature with respect to configuration times that could serve as a baseline against which we could compare our design's performance. According to the Nielsen Norman group, users are tolerant of longer wait times and delays if and when they can see progress and understand the cause for the delay [82]. Our design offers a meaningful physical transformation, and users can track progress visually, owing to this and a discussion with our collaborators at Cornell University, we settled on two minutes as the maximum total configuration time for the larger transformations such as the bed and the table and a minute and thirty seconds for the smaller configurations such as the chairs and shelf.

Once our design specifications were finalized, the task was to engineer a 'slice' at full scale, within the scope of the goals from the survey, and the engineering constraints of the specifications. The details of the prototype design are further elucidated in the following sections of this chapter.

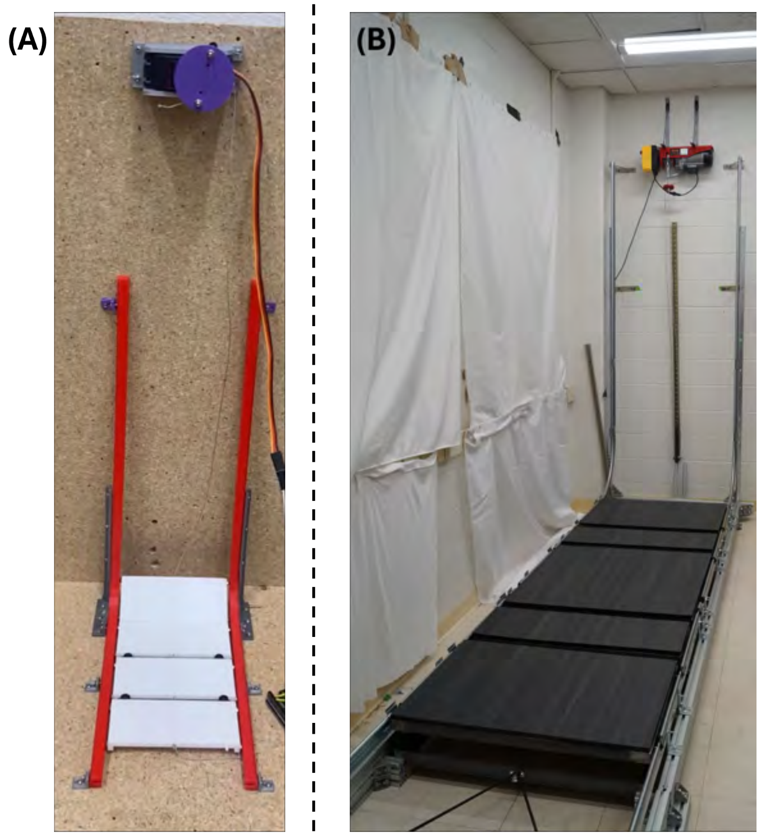


Figure 2.6: Left: (A) Early small scale prototype; Right: (B) final full scale prototype for comparison.

2.6 Full scale prototype design and realization

The fundamental concept revolves around a series of 'active' panels mounted on tracks embedded within the room. The panels are interconnected via linkages and form a chain, and are equipped with wheels allowing them to traverse along the tracks. The panels should be capable of actuating on and off the tracks as required, giving the user the illusion (and reality) of the floor and wall raising and lowering. We further leverage these features to enable the panels to dynamically reshape to form the desired furniture configurations such as tables, chairs, or beds based on inhabitant input and needs.

Once we finalized the overarching design direction, the first step in the design process was to resolve the track system's architecture, which was foundational to the system as a whole. In lieu of re-inventing the wheel and designing a completely novel track system (which presents challenges such as wheel-track friction), we chose to use garage door tracks and matching rollers as wheels.

This alleviated the additional engineering burden and any unexpected issues that might arise with it.

We did consider other alternatives such high-angle conveyor or vertical sidewall conveyor belts. This proved to be too expensive and the belts have a large form factor making them unsuitable. We also considered guided roller tracks which could be functional in the horizontal or vertical plane. However, they are not conducive to functioning as a unit as the connections between the horizontal and the vertical tracks have to be at 90°which in turn prevents the panels from smoothly transitioning up and down the wall. The garage door tracks proved to be the best solution overall, owing to their relatively small form factor and low cost in comparison to the alternatives.

The next design problem we needed to address was panel traversal along the tracks. Early in the design phase, we considered converting the panels at each end of the chain to "engines" equipped with motorized wheels to drive the panels up and down the tracks as needed. However, we opted against this approach after a brief qualitative analysis, which suggested that the overall torque required to drive the panels along the tracks, especially up the wall, would have been sufficiently large to make it unfeasible. Instead, we opted to go with an electric winch system designed for high load applications. In this solution, the cable to the panel at the end of the chain would be attached and the winch drive the panels along the tracks as required.

The subsequent step in the overall prototype design was to prove that this concept works in the small scale. To do so we designed and 3D printed a pair of garage door tracks (one-tenth scale) and a series of panels, and used a standard MG995 servo motor to function as a winch. The small scale prototype performed well, and overall validated our design while providing insight we would not have had without the small scale prototype. A key insight we gained through this exercise was the need for the panels to be spaced out in order to avoid pinching as they traversed up the wall. Fig.2.6 (A) illustrates the early small scale prototype, Fig.2.6 (B) final full scale prototype for comparison.

The completed track set includes the following parts: (1) A pair of two inch horizontal garage door tracks with 15" radius; (2) two pairs of 2" vertical garage door tracks, both sets of tracks are 0.075 gauge steel designed for for 7 ft high doors; and (3) 2 inch steel (actual roller width 1-3/4") garage door rollers with a four inch Zinc Stem.

We selected a 'VEVOR' 1320lbs Wireless Electric Hoist 1150W 110V, as the winch with a single Cable lifting height 40ft. The winch is equipped with braided steel cable for added stability and load capacity. The winch offers two modes of operation, a single line lift capable of lifting 660 lbs at 32 ft/min, with a max height of 39.4 ft and a double line lift capable of lifting 1320 lbs at 16 ft/min, with a max height of max height: 19.7 ft.

In addition to the winch itself, we deigned a custom carriage machined out of 12 inch long (0.75 inches thick) alloy steel. Holes were strategically cut out to house eight 0.25 inch thick wheels and their axles (1.3125 inches long and 0.5 inches in diameter) as well as a pair of pulleys (1.5 inch diameter). The winch wire was fed through the pulleys and then attached to the panels. This was engineered to ensure a gradual curvature of the winch wire, as sharp angles would cause the panels to lift up and out of the tracks as the panels were pulled up. The carriage runs up and down the wall on a 1.625 inch wide steel channel, as a unit they form the carriage system as. Figure 2.7 illustrates the carriage system and a dimensioned drawing of the carriage is provided in Appendix A. The winch along with the carriage system forms the overall winch system.

2.7 Panel Design

Having successfully engineered the track system and the winch system for panel traversal, our subsequent efforts were directed towards engineering the robotic panels themselves. Our first iteration of the panel system consisted of a series of rotating hinged panels interconnected via self-locking 90°hinges, with the panel rotation facilitated by linear actuators. Each desired furniture configuration required at least five panels, each with a pair of linear actuators. The two outer panels were inactive and housed the base of the linear actuators underneath them, while the inner two panels housed the head of the linear actuators. The fundamental idea was that as the linear actuators extended, the inner panel pair would rotate upwards and lock once they reach 90°, dragging the middle panel up with them in the process forming a shape not too dissimilar to a square waveform.

Once we started building and qualitatively testing the prototype, we realized that we needed to add a sliding rail to each panel housing the actuator heads in order to give the actuators enough leeway to complete the 90°rotations. We quickly came to the realization that while the design seemed to be a sound solution in theory, in practice the fully actuated panels would not be capable of bearing high enough loads to support human weight or everyday human activities.

We considered other actuation techniques such as a motorized truss-based hoist system wherein high torque hoists would be mounted on tracks on the ceiling. The hoists would suspend

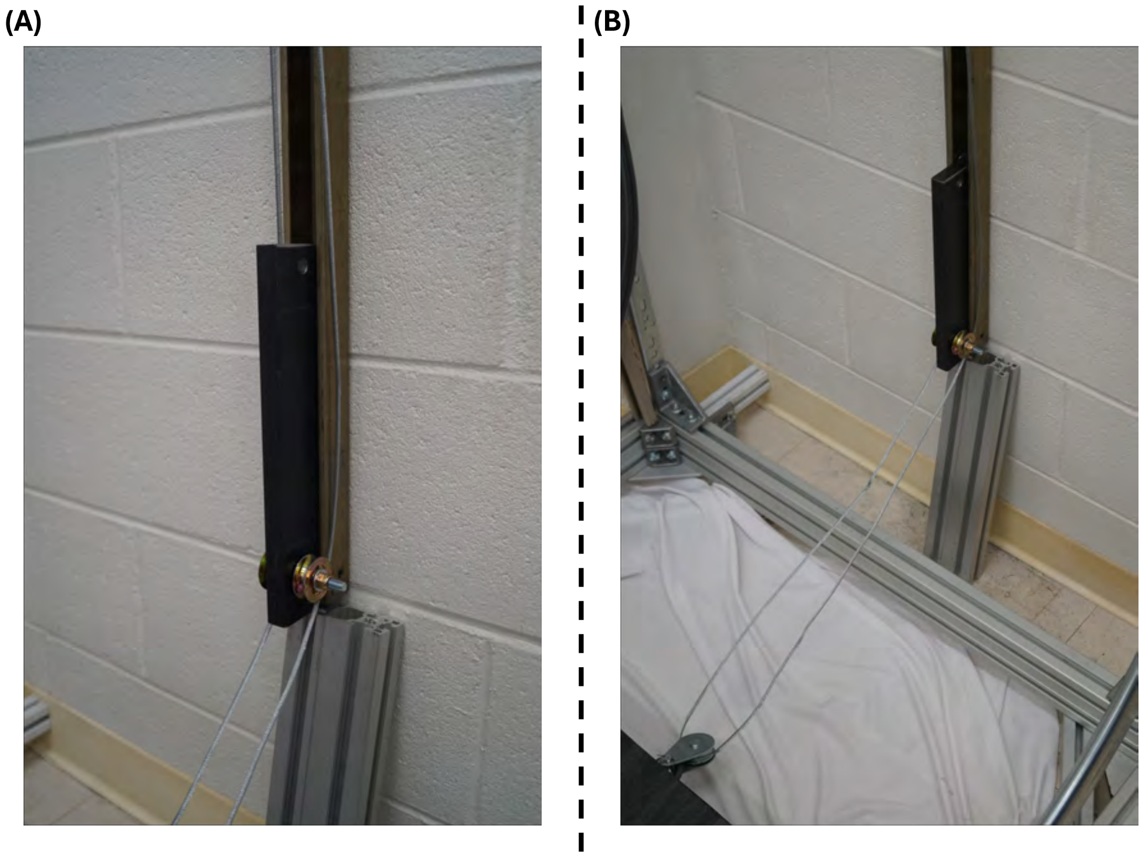


Figure 2.7: The Carriage System: Left: (A) A close up view of the carriage system; Right: (B) A zoomed out perspective illustrating the gradual angle of the winch wire.

lifting cables that could be attached to the panels, and the cables then lift them to form various configurations. However, this idea required significant user intervention, such as detaching and attaching the cables as well as any support stands as would be required to support the furniture configurations. This fell short from an user experience (UX) perspective.

In addition, the automation of all the aforementioned parts notwithstanding, the engineering effort required to realize this design would have been substantial. While we excluded these actuation techniques through qualitative analysis, there is space for future researches to re-explore these techniques to quantitatively assess them, and compare them to the prototype developed herein. This realization prompted us to reconsider the fundamental panel design, and led to the idea of 'active' panels, an actuation system based on scissor lifts. As illustrated in Table 2.2, the scissor lift actuation technique met all four of our basic design criteria. The design and realization of the pivot

Actuators	Actuation Type	Load Bearing	Form Factor	UX	Engineering Load
High Torque Motors	Rotational	✗	✗	✓	✓
Truss Based Hoist Actuation	Vertical	✓	✓	✗	✗
Scissor Lift (Active Panels)	Vertical	✓	✓	✓	✓

Table 2.2: Actuator Considerations.

to active panels is further elucidated in the subsequent sections of this chapter.

2.7.1 Pivot to Active Panels

While the core of the panel system remained the same, i.e. a series of interconnected panels traversing along the tracks, we elected to re-design the basic actuation technique. This led to an 'active' panel design wherein the panels have a built in actuation mechanism which enables the panels to raise and lower as needed to form the desired furniture configurations. Our re-designed panel design was driven by a scission lift mechanism. Traditionally, scissor lifts are large and lack a small form factor, especially in their un-actuated or closed form. However, for our application we needed a scissor lift capable of having a maximum closed form factor of 8 inches, a minimum fully extended height of 15 inches and a maximum of 30 inches, promoting the design and construction of a series of custom scissor lift mechanisms.

The overall panel system in the final full-scale prototype comprises a chain of five panels in total, with three active and two inactive panels. The outer two panels are active, and capable of extending up to 18.75 inches, and are designated to function as chairs. (One also functions as a shelf.) The two inner panels are inactive, and function as foot rests. Finally the central panel is capable of extending up to 24.25 inches and is designated as a table, and is also capable of functioning as a chair if needed. All the panels are 35.75 inches wide, the panels designated as chairs are 25 inches long, the panel designated to be the table is 37 inches long, and the two inactive panels are each 12 inches long.

Each panel comprises a pair of frames, the top frame and the bottom frame. Figure 2.8 illustrates the side profile of a panel in its two configurations. The top frame houses the four wheels that allow motion along the tracks, and sits on the tracks. The bottom frame is suspended below the top frame, and is parallel to it.

The fundamental concept is that, as the panels were actuated, the bottom frame would actuate downwards until it made contact with the floor, thus providing a firm base. Meanwhile the

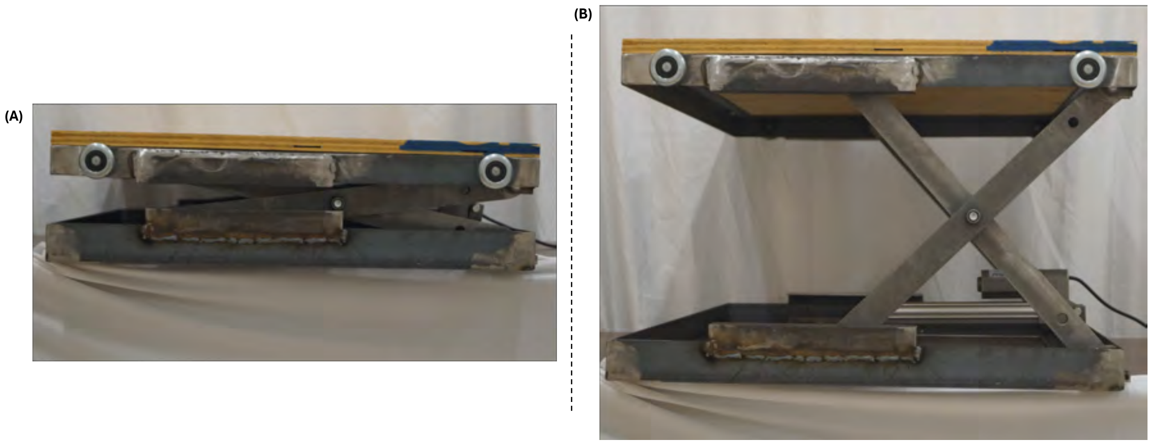


Figure 2.8: Side profile of a panel in it's 2 configurations; Left: (A) Closed configuration, Right: (B) Fully extended configuration.

top frame would actuate vertically off the tracks - wheels rising through strategically located gaps in the top of the track - until it reaches its maximum extension to create the necessary furniture configurations. When ready to retract, the top frame would be lowered until it made contact with tracks. Once it does so, the bottom frame naturally lifts off the floor until fully closed. A detailed breakdown of the panel design is presented in the following subsection.

2.7.2 Panel Architecture

Figure 2.9 depicts a side profile of a panel and its major components: top (Fig. 2.9 A) actual prototype with major components marked up, bottom (Fig. 2.9 B) model view with a list of major components. Each active panel is made up of ten major components as illustrated in Fig. 2.9 B. The top and the bottom frames of were welded using low-carbon Steel 90 °angle iron with 1/8th inch wall thickness. The top frame has 1.5 inch outside size while the bottom from has 2 inch outside size. The scissor arms were machined out of 1.5 inches wide x 0.5 inches thick A572 alloy steel. All the mounting brackets were custom designed and machined out of A572 alloy steel and were welded on to the frames. A low carbon steel rod (0.5 inch diameter) was used for the axles, with notches cut out at the each end to house the wheels. High load ball bearings (0.5" shaft diameter) were used for wheels, and external retaining rings (0.5 inch outer diameter) were used to hold the wheels in place.

The linear actuator head mounting bracket and the wheel tracks were made out of low-carbon steel rectangular tubes with 0.065" wall thickness, and 1 inch x 1 inch outside size. In the

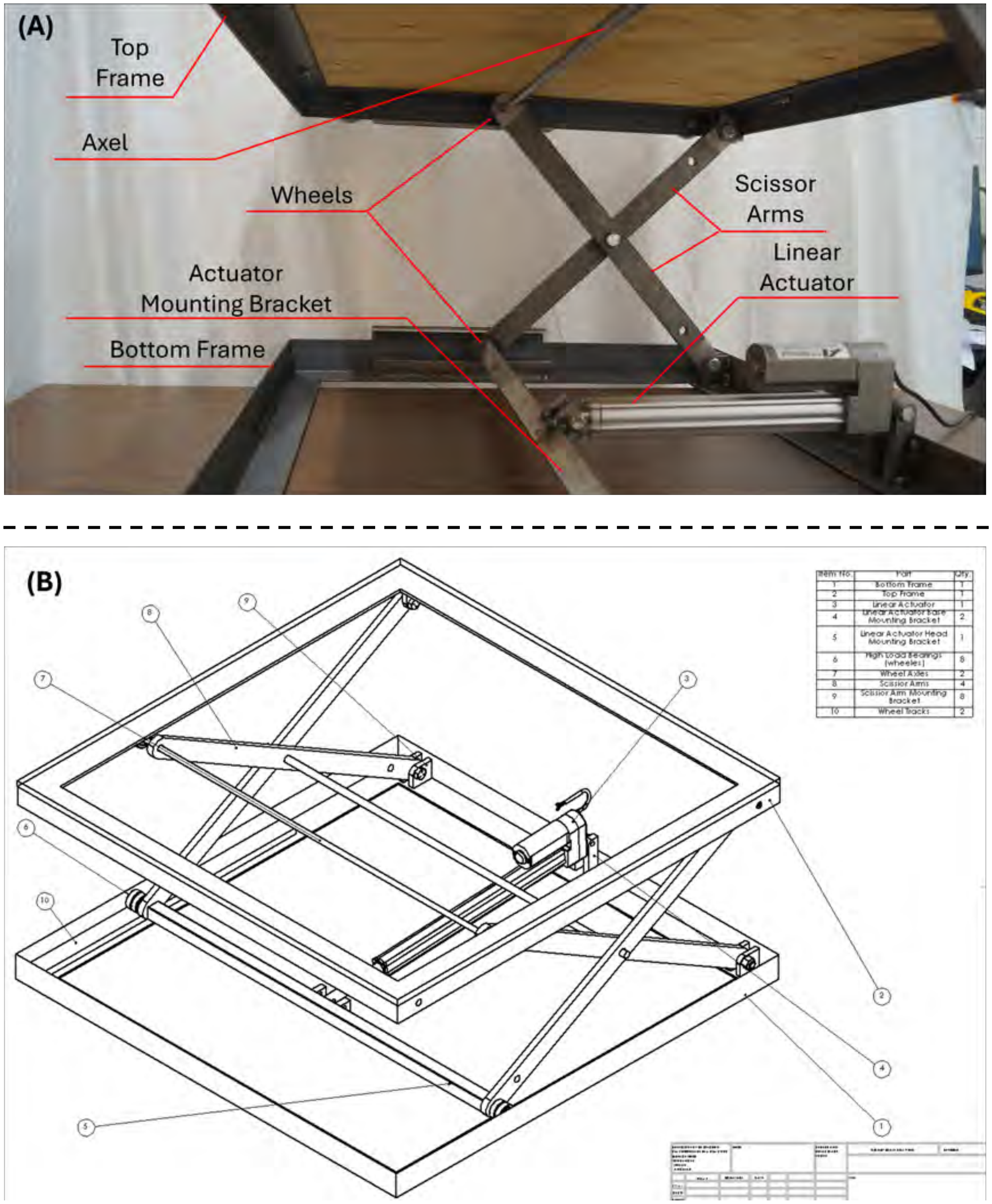


Figure 2.9: Side profile of a panel and it's major components; Top (A) Prototype with Major Components Marked up: Bottom (B) Model View with a list of major components.

Part	Material Link
Top Frame	https://www.mcmaster.com/9017K484-9017K48/
Bottom Frame	https://www.mcmaster.com/9017K494-9017K49/
Scissor arm	https://www.mcmaster.com/3706N52-3706N198/
Ball Bearings	https://www.mcmaster.com/7806K716/
High Load Ball bearing	https://www.mcmaster.com/2780T19/
Scissor Arm Mounting Bracket Material	https://www.mcmaster.com/3706N42-3706N171/
Actuator Base Mounting Bracket Material	https://www.mcmaster.com/3706N52/
Actuator Head Mounting Bracket Material	https://www.mcmaster.com/6527K174-6527K17/
Wheel Axles	https://www.mcmaster.com/8920K155-8920K154/
Retaining Ring	https://www.mcmaster.com/91590a122/
Linear Actuator - 14" Stroke Length	https://www.firgelliauto.com/products/super-duty-actuators?variant=39956755021895
Linear Actuator - 8" Stroke Length	https://www.firgelliauto.com/products/super-duty-actuators?variant=39956754825287
Plywood	https://shorturl.at/cnYmO
Springs	https://www.mcmaster.com/5108N652/
Chain Links	https://a.co/d/hQy2Tf1
Channel (carriage system)	https://www.mcmaster.com/9001K59/
Brass (carriage system)	https://www.mcmaster.com/1784N11/
Sheet metal (carriage system)	https://www.mcmaster.com/3706N132/
Jamb Brackets	https://a.co/d/1Mejh0l
Power Supply	https://a.co/d/aDnPHV6
Motor Controller	hhttps://a.co/d/aDnPHV6
Arduino Mega 2560	https://www.mcmaster.com/3706N132/
Winch	https://a.co/d/aKsfw5A
Garage Door Tracks- 1	https://ddmgaragedoors.com/parts/part/TRH-20715-075.html
Garage Door Tracks- 2	https://ddmgaragedoors.com/parts/part/TRV-207-075.html
Garage Door Rollers	https://ddmgaragedoors.com/parts/part/RO-S2410Z.html

Table 2.3: List of raw materials and parts used.

final design a pair of thrust ball bearings (for 20 mm shaft diameter, 35 mm outer diameter) were placed at the central axis point of each scissor arm pair and were held in place using standard hex head screw nuts and bolts. This allowed us to eliminate the central axle and reduce weight.

Feedback-enabled super duty linear actuators from Firgelliauto (450 lbs dynamic and static force) were used to drive the system, the panel capable of extending 24.25 inches utilizes an actuator with a 14 inch stroke length, while the panels that extend to 18.75 inches made use of an actuator with 8 inch stroke length.

The final addition to the panels were the garage rollers. Four holes in total (two on each side) were drilled into the short side of the top frames to house the rollers. The stems of the rollers were cut down to an inch from their original size and then welded on to the frames. The wheels were set 20 and 30 inches apart on the smaller and larger panels respectively, and 8 inches apart on the inactive panels (center to center). Dimensioned drawings of all the major components are included in Appendix A for reference. Table 2.3 is a list of raw materials used to fabricate the panels.

The two key factors to the panels having a small closed form factor are; (1) their length: the length provides the actuators with the extra traveling distance required to achieve the small closed form factor and (2) the length of the scissor arms, which are dimensioned to be 5 inches shorter than the total length of their corresponding panels. The panels are designed to be scalable as a unit enabling future researchers and designers to resize the panels as needed to suit their specific design requirements and applications.

The inactive panels are a pair of frames, without actuators, spaced out to match the closed size of the active panels. The top and the bottom frames of the inactive panels are held apart via 4 pieces of metal welded vertically between them.

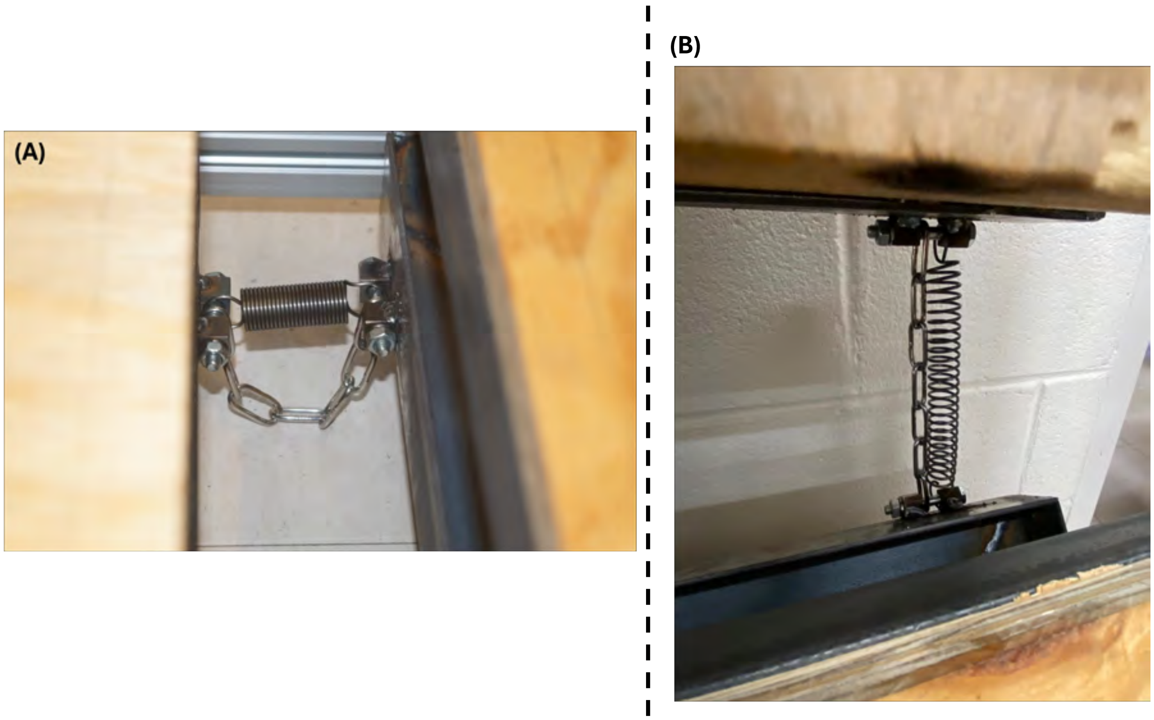


Figure 2.10: Spring and Chain linkage system used to connect the panels: Left (A) Compressed state; Right (B) Extended state.

All panels are connected to their neighbor via a pair of steel extension springs with loop ends and seven inch long galvanized steel chain links as shown in Figure 2.10, which illustrates a spring in its compressed and extended state. Through early testing we realized that the panels needed a minimum of six inches of clearance between them in order allow the required rotations of the panels as they travel up and down the tracks. However, from a practical user perspective, a six inch gap between the panels in the 'floor' configuration was undesirable, as it would hinder the user's ability to traverse it on foot.

This led us to selection of springs which are three inches long in their compressed state and extend up to 6.5 inches, giving the panels enough room to comfortably travel up and down the

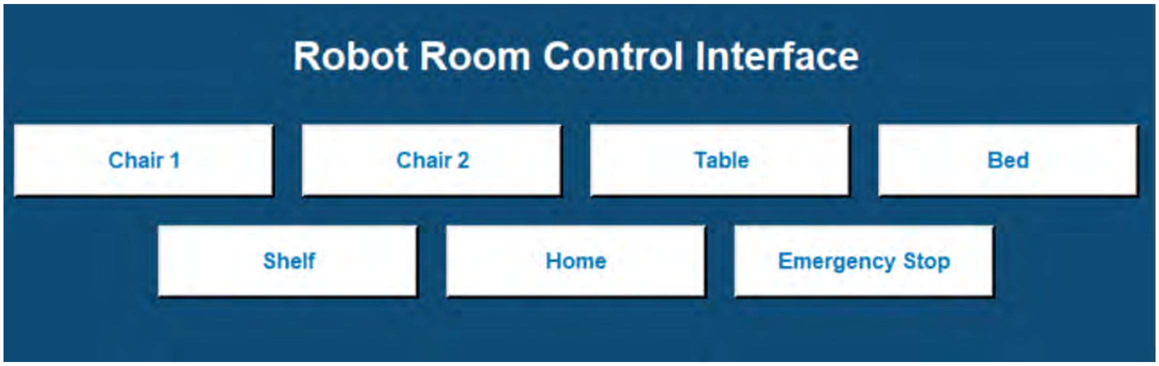


Figure 2.11: Graphical User Interface.

tracks. The galvanized steel chain was included to reduce some load on the chain and to keep the springs in place in their fully extended state, as well as act as a fail safe in an event that the springs collapsed.

2.8 Control Unit

The overall control unit is split into two parts: winch control, which is responsible for panel traversal along the tracks; and configuration control, which is for facilitating the various furniture configurations.

Based on the results of the survey summarized earlier in the chapter, users overwhelmingly wanted more direct control and less autonomous behavior. Owing to this we chose to give users complete control of the panel traversal along the tracks. Panel traversal is controlled via a wireless remote, with four main operating buttons, 'Start' to turn the system on, 'Stop' to turn the system off, 'Up' to move the the panels vertically up the tracks, and 'Down' to bring them back down to their starting position.

The panel actuation to produce the desired configurations is controlled via an Arduino Mega. Each linear actuator is connected to the Arduino via a BTS7960 43A high power motor driver module. Users are able to select their desired furniture configuration via a Graphical User Interface (GUI) operated on a computer (Fig. 2.11), which then triggers the panel actuation. The actuators are powered through a 12VDC/40A power supply. A picture of the control circuit embedded within the system is illustrated in Figure 2.12 and an electrical schematic diagram of the configuration control circuit is illustrated in Figure 2.13. The code used to control the system and generate the

GUI are presented in Appendix B and Appendix C respectively. The control methodology developed offers increased flexibility, allowing future researchers to independently control each actuator, and the freedom to add new sensors as they see fit.

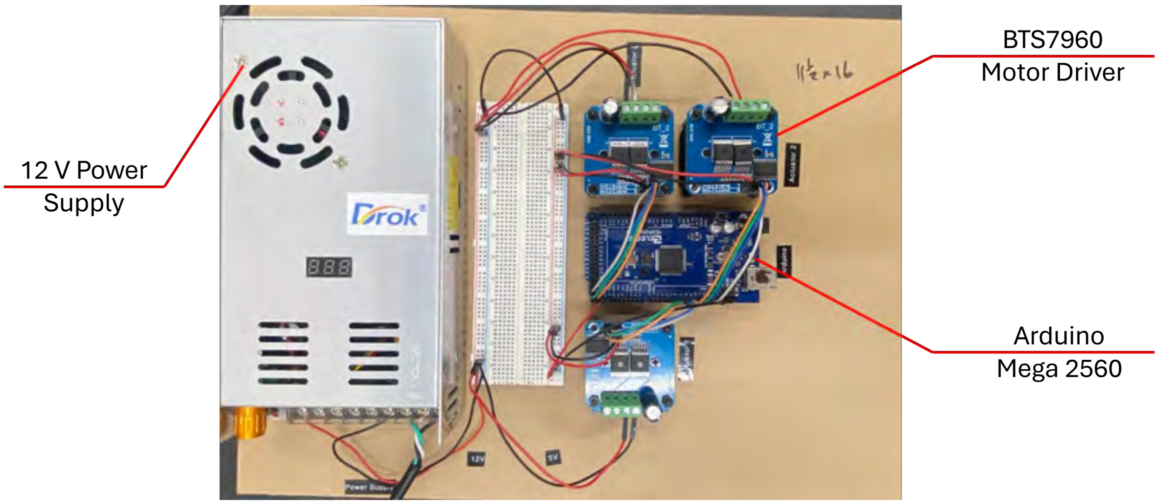


Figure 2.12: Configuration control circuit.

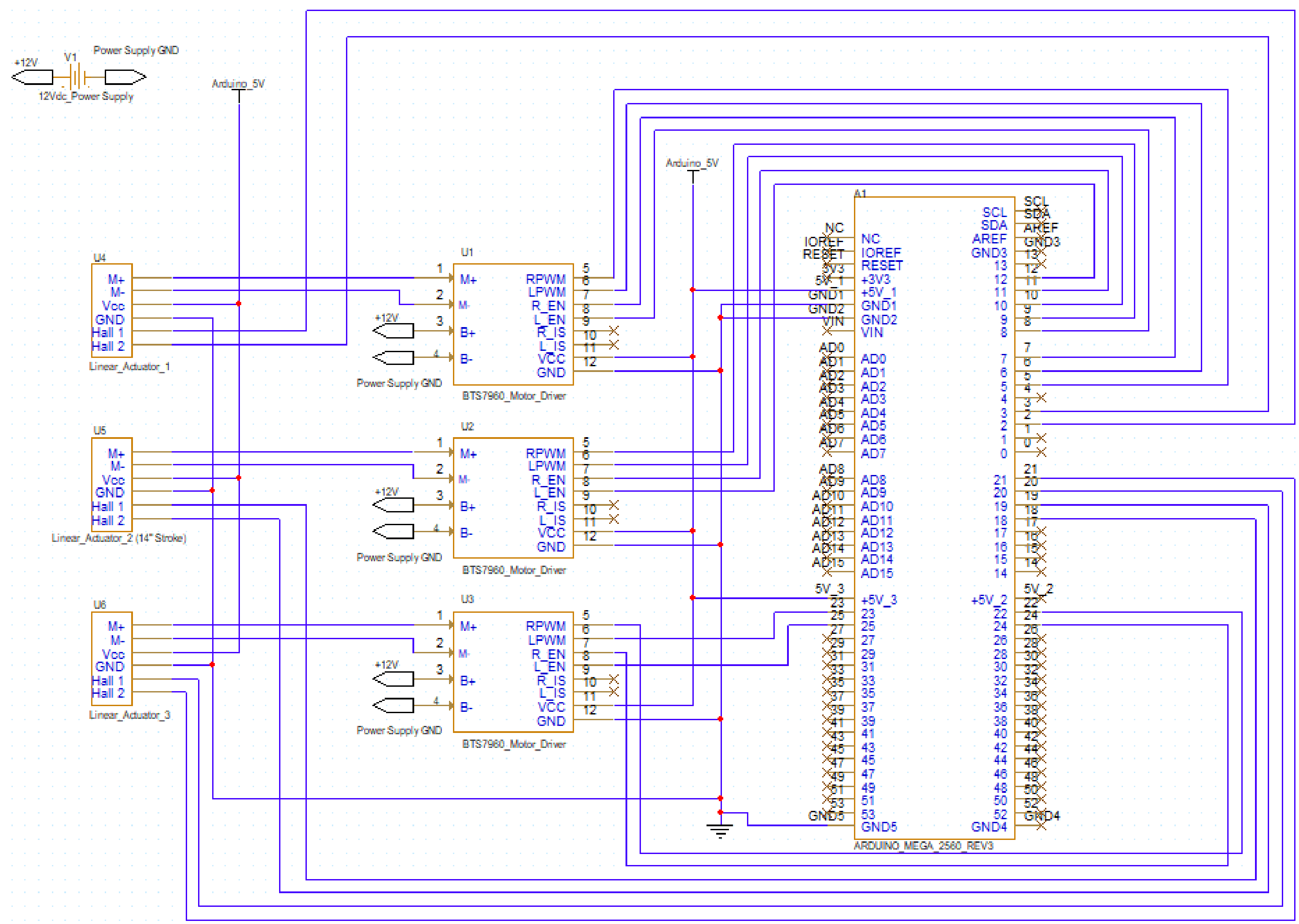


Figure 2.13: Configuration control Schematic.

2.9 Final Assembly

The final fully assembled robot consists of 4 major components, namely the track system, the winch system, the panels, and the internal control unit. Figure 2.14 illustrates the fully assembled robot with all the visible major components labeled. The Vertical portion of the tracks were adhered directly to the wall using 2 pairs of standard 'L' brackets for support and to aid in load bearing as the winch pulls the panels up the wall. The horizontal portion of the tracks rest on a pair of 80/20 double aluminum extrusion beams. The tracks were connected to the extrusion using 5 jamb brackets on each side. Three inch slots were cut out at strategic locations along the tracks to allow the panels to actuate on and off the tracks.

Overall, the cost of the raw materials required for manufacturing the bigger panel was $792.98, $722.39 each for the 2 smaller panels and $89.75 each for the inactive panels. Adding up the cost of all the materials and the individual parts required for the fully assembled prototype, the final pre-tax cost was $3943.92.

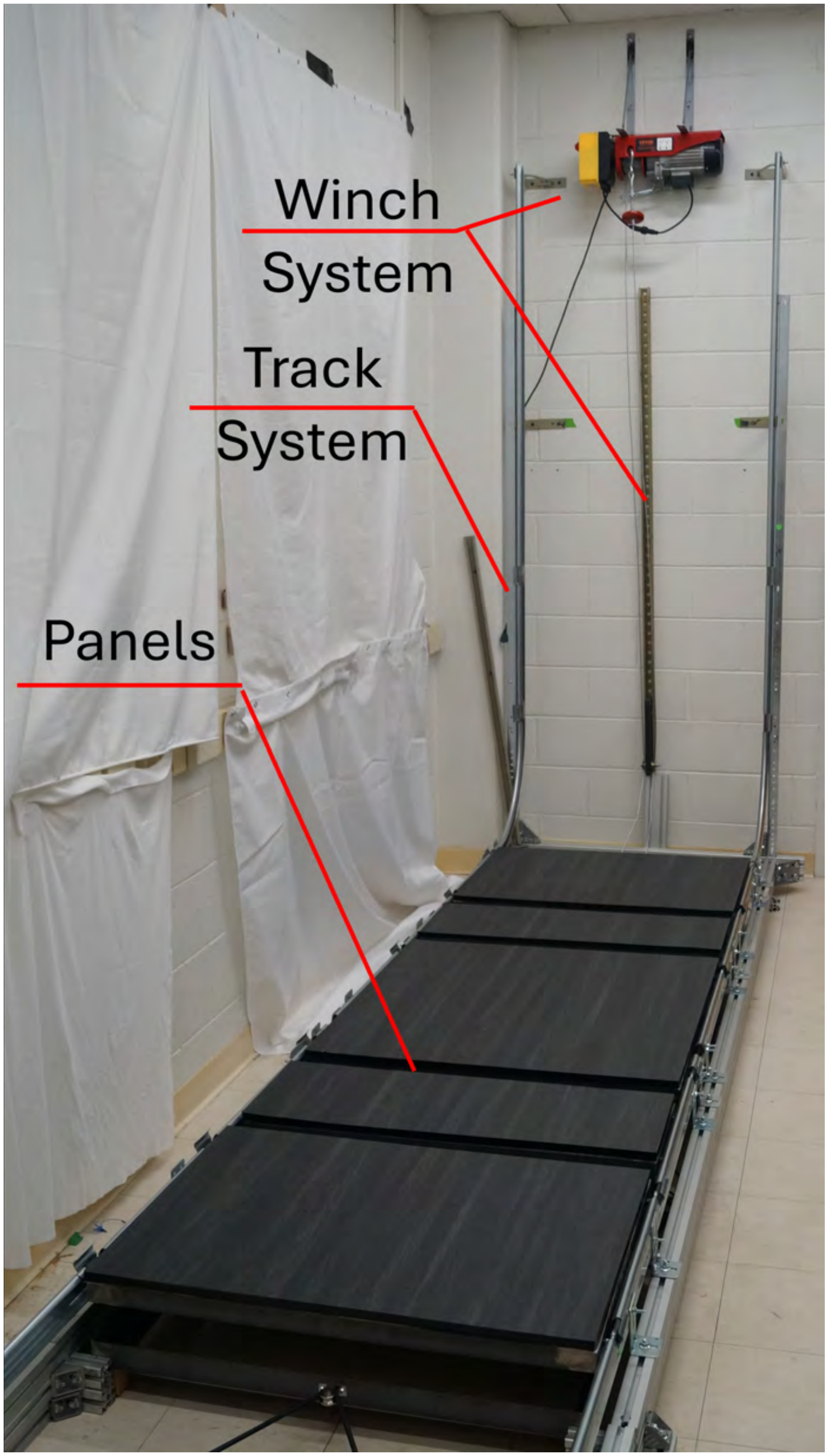


Figure 2.14: Fully assembled Full scale prototype with all the visible major components labeled.

Chapter 3

Experiments And Results

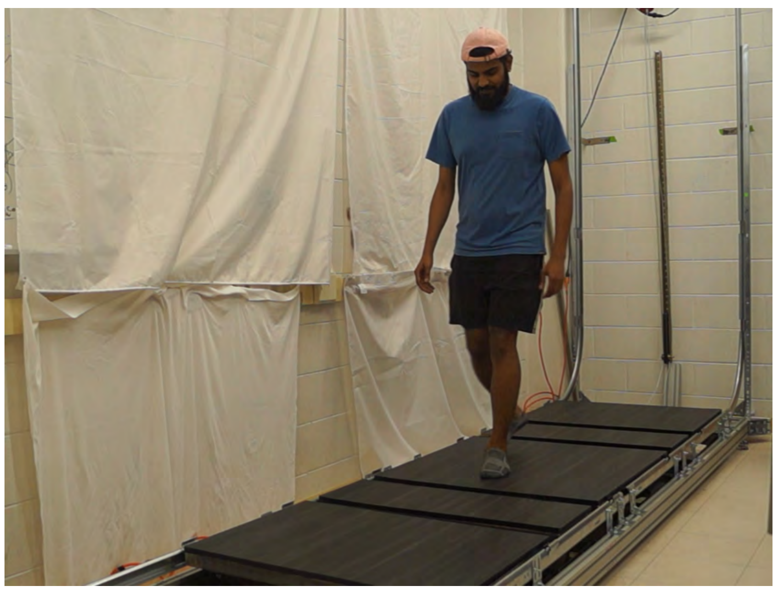


Figure 3.1: Robot system in its natural floor configuration.

During the design and conceptualization phase we aimed to produce four distinct types of furniture: a table, chairs, a bed, and a shelf, and subsequently three main configurations that utilize these furniture items to support human activity. The configurations we set out to achieve are as follows: a combination of table and a pair of chairs; a bed; and a shelf. Figure 3.1 illustrates the robot system in its natural floor configuration. Figure 3.2 illustrates the robot system in the 'table and chair(s)' configuration supporting a pair of domestic activities, namely, working (top) and eating dinner (bottom). Figure 3.3 illustrates the robot system in the bed configuration and Figure 3.4

presents the shelf configuration. A video demonstration of the system in action is presented in an an accompanying video [83]

Figure 3.2: Robot system in the 'table and chair(s)' configuration supporting a pair of domestic activities, namely, working (top) and eating dinner (bottom).

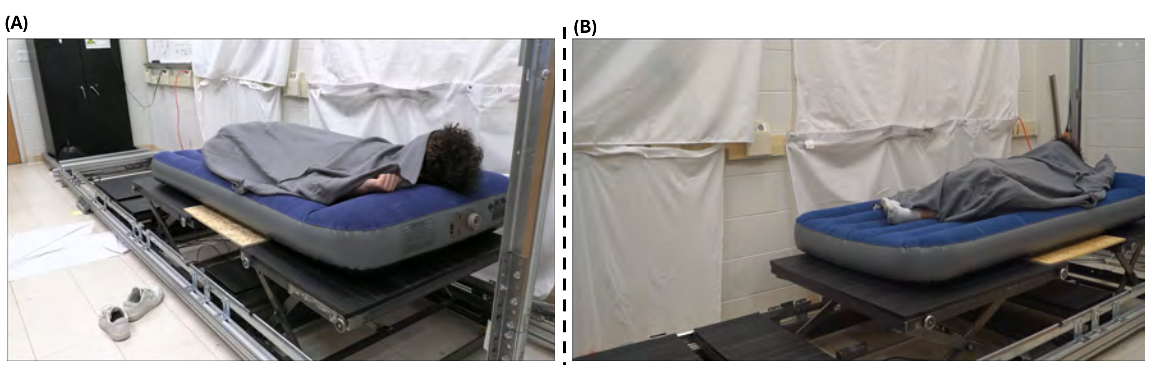


Figure 3.3: Robot system in the bed configuration.

Once these configurations were successfully realized in hardware, we performed a series of experiments to test and validate the prototype and provide a series of qualitative results that future researchers can refer to, compare and build on. We categorized our experiments into two main categories: first, repeatability, to test and learn how consistent the robot was in producing these configurations and performing its functions, along with how long the robot took to achieve

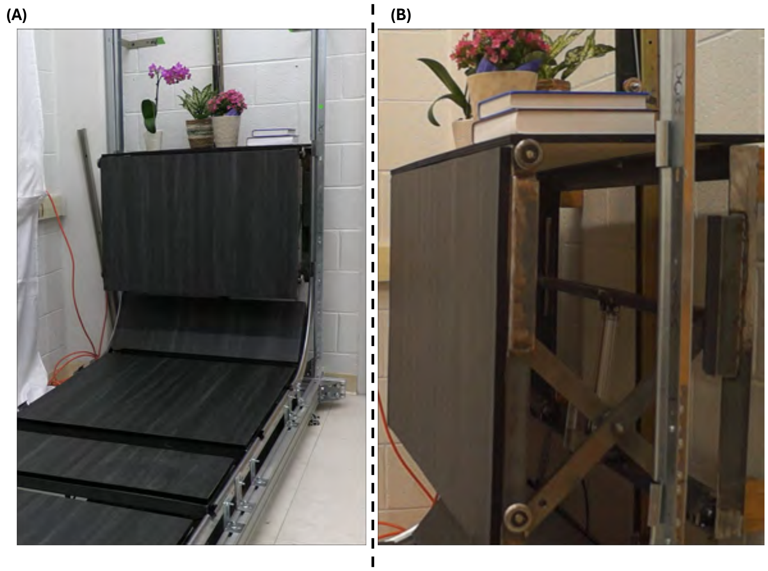


Figure 3.4: Robot system in the shelf configuration, Left; (A) front profile; Right; (B) Side profile.

them. The second category of experiments were load bearing experiments to measure the system's performance in terms of its capacity to bear load, i.e. support human activity. We compared the findings from these experiments against our early design phase hypothesis and goals.

3.1 Repeatability Experiments

3.1.1 Track Traversal Repeatability Experiments

We first defined a workspace within the tracks, i.e. set an upper limit: the maximum height the panels should travel vertically up the tracks; and a lower limit, the maximum distance the panels should travel on the horizontal section of the tracks. A point to note is that the lower limit also serves as the starting position for the panels.

A pair of experiments were targeted at evaluating the panel's traversal along the track. Small circular green labels (19.05mm (0.75in) diameter) were attached to both the upper and lower limits on the track, with the target being the center of the label. The goal of the experiments was to repeatedly position the rear right wheel of the furthest panel and the front right wheel of the closest panel (from the perspective of a user standing at the end of the horizontal portion of the tracks) to the target and then measure the distance between the center of the wheels and their corresponding targets in an effort to measure the system's positioning accuracy. We also timed how long the panels

Run	Distance From Target (mm)	Distance From Target (in)	Time to Reach Target (seconds)
1	6	0.24	7
2	1	0.04	10
3	2	0.08	11
4	9	0.35	10
5	8	0.31	11
6	1	0.04	9
7	6	0.24	9
8	1	0.04	9
9	5	0.20	10
10	6	0.24	8
Mean	4.5	0.18	9.4

Table 3.1: Vertical Traversal Experiment.

took to reach their respective targets. Each experiment was repeated ten times and the results are presented below.

Table 3.1 presents the results of the vertical traversal experiments. Over ten runs, the panels were 4.5mm (0.18in) off the center of the label on average, and the average time it took them to reach said target was 9.4 seconds. Similarly, Table 3.2 presents the results of the horizontal traversal experiments. Over ten runs, the panels were 6.05mm (0.24in) off the center of the label on average, and the average time it took them to reach said target was 9 seconds. Analyzing the results, the panels were more slightly accurate traversing up the tracks, while the the time it took for them to reach the target on the horizontal portion was fractionally less.

Following these experiments, we placed a pair of physical blocks on both the upper and lower limits of the tracks, physically restricting them and preventing the panels from moving past that point. We then repeated the experiments, the panels showed improved accuracy in terms of docking and the panels hit the target (center of the green circular label) accurately, with no play or bouncing on any run.

3.1.2 Configuration repeatability Experiments

The next series of experiments were targeted at the repeatability of the configurations and furniture actuation. For the sake of the experiments, the two smaller panels were labeled panels 1 (closest panel) and 2 (farthest panel) and the larger panel was labeled panel 3 (middle panel). Each panel was raised off the track to its full height and then lowered back on to the tracks to its natural collapsed configuration. The time time it took each panel to fully extend and then collapse

Run	Distance From Target (mm)	Distance From Target (in)	Time to Reach Target (seconds)
1	12	0.47	10
2	5	0.20	10
3	6.5	0.26	10
4	5	0.20	10
5	10	0.39	8
6	3	0.12	10
7	6	0.24	8
8	2	0.08	9
9	7	0.28	10
10	4	0.16	8
Mean	6.05	0.24	9

Table 3.2: Horizontal Traversal Experiment.

was recorded. This exercise was repeated for a total of ten trials for each panel, and the results are reported below.

Table 3.3 presents the results of the repeatability experiment performed on panel 1. On average the panel 1 took 25.11 seconds to fully expand to its maximum height (18.75 inches from the ground) and 26.95 seconds to collapse on to the tracks, with 52.06 seconds being the average time it took the panel to fully configure i.e. expand to its maximum height and them collapse back down to its original form factor.

Panel 2 took 25.54 seconds on average to fully expand to its maximum height (18.75 inches from the ground) and 28.14 seconds to collapse on to the tracks, with 53.68 seconds being the average time it took the panel to fully configure. On average Panel 2 took 1.62 seconds more than panel 1 to fully configure. Table 3.4 illustrates the results of the experiments performed on panel 2.

As panel 2 is designed to function as a shelf, a configuration in which it actuates to extend horizontally off the wall, the same experiment was repeated to test the performance of the panel in its shelf configuration. Table 3.5 illustrates the results of the experiments performed on panel 2 in it's shelf configuration. In this configuration, panel 2 took 24.73 seconds on average to fully expand to its maximum depth (18.75 inches from the wall) and 26.14 seconds to collapse onto the tracks, with 50.87 seconds being the average time it took the panel to fully configure. An interesting outcome of these experiments was that the two chairs on average had a total configuration time of 52.87 seconds, while the shelf was 2 seconds faster. (Note that gravity is a factor in the chair deployment, while shelf motion is perpendicular to gravity.)

The results of experiments performed on Panel 3, i.e. the larger of the three panels, are

Run	Time to Expand (sec)	Time to Collapse (sec)	Total Configuration Time (sec)
1	25.84	26.00	51.84
2	25.39	27.33	52.72
3	25	27.53	52.53
4	24.86	27.83	52.69
5	25.24	27.58	52.82
6	25.24	27.18	52.42
7	24.72	27.06	51.78
8	25.09	26.71	51.80
9	24.88	27.78	52.66
10	24.87	24.46	49.33
Mean	25.11	26.95	52.06

Table 3.3: Panel 1 Repeatability Experiment.

presented in Table 3.6. On average the panel 3 took 33.88 seconds to fully expand to its maximum height (24.25 inches from the ground) and 36.30 seconds to collapse, with 70.17 seconds being the average time it took the panel to fully configure. On average the two smaller panels took 52.87 seconds to fully configure, where panel 3 on average took an extra 17.3 seconds owing to its larger size and stroke.

In addition to the standard full extension experiment, an additional experiment was performed to test how long the panel needed to reach a height of 18.75 inches (the same as the max height of the smaller height panels) as the bed configuration requires all three panels (or some combination of one large panel and one of the smaller panels) to be at the same height. On average the panel took 16.91 seconds to expand to the new height and 18.38 seconds to collapse with 35.29 being the average time it took the panel to fully configure. The results of this experiment are presented in Table 3.7.

3.2 Load Bearing Experiments

The last set of experiments were aimed at evaluating the system's load bearing capacity. In the fully collapsed floor configuration, the system was able to handle a total of 530 lbs. Of the total weight added to the system 320 lbs of it was classified as "active weights", with this weight added through a pair of human subjects weighing 190 lbs and 130 lbs walking across the length of the panel. The remaining 210 lbs were added through assorted weights distributed across the system along with the active weights.

Run	Time to Expand (sec)	Time to Collapse (sec)	Total Configuration Time (sec)
1	26.40	28.26	51.84
2	25.58	28.16	52.72
3	25.59	28.19	52.53
4	25.44	28.14	52.69
5	26.01	28.16	52.82
6	25.30	28.20	52.42
7	25.21	28.04	51.78
8	25.23	28.08	51.80
9	24.20	28.01	52.66
10	25.41	28.16	49.33
Mean	25.54	28.14	53.68

Table 3.4: Panel 2 Repeatability Experiment.

Run	Time to Expand (sec)	Time to Collapse (sec)	Total Configuration Time (sec)
1	24.78	26.24	51.02
2	24.83	26.21	51.04
3	25.01	26.26	51.27
4	24.84	26.18	51.02
5	25.03	26.19	51.22
6	24.76	26.19	50.95
7	24.56	25.94	50.50
8	24.44	25.91	50.35
9	24.58	25.99	50.57
10	24.48	26.26	50.74
Mean	24.73	26.14	50.87

Table 3.5: Panel 2 Repeatability Experiment, Shelf Configuration.

Run	Time to Expand (sec)	Time to Collapse (sec)	Total Configuration Time (sec)
1	34.31	37.13	71.44
2	34.4	36.76	71.16
3	34.23	36.91	71.14
4	33.79	37.24	71.03
5	33.63	37.39	71.02
6	34.09	35.58	69.67
7	33.82	35.48	69.30
8	33.69	35.55	69.24
9	33.36	35.43	68.79
10	33.43	35.58	68.91
Mean	33.88	36.30	70.17

Table 3.6: Panel 3 Repeatability Experiment.

Run	Time to Expand (sec)	Time to Collapse (sec)	Total Configuration Time (sec)
1	16.64	18.24	34.88
2	17.57	18.86	36.43
3	16.71	18.11	34. 82
4	16.84	18.49	35.33
5	17.51	18.38	35.89
6	16.58	18.34	34.92
7	17.66	18.46	36.12
8	16.49	18.39	34.88
9	16.51	18.36	34.87
10	16.54	18.21	34.75
Mean	16.91	18.38	35.29

Table 3.7: Panel 3 Repeatability Experiment, 18.75 inches expansion height to match the other panels for the bed configuration.

The next step was to test each individual panel's load bearing capacity in its fully actuated state. Each panel was able to handle a total of 400 lbs. Here, 190 lbs was "active weight" added via a human being sitting on the panel and the remaining 210 lbs added via assorted weights. For the bed configuration where all three panels work in unison, the system was able to handle 400 lbs as a unit. For the shelf configuration where panel 3 actuates out of the wall, the panel supported a total of 100lbs.

A point to note: the limits listed here are not the maximum limits of each configuration. We believe that the panels and configurations are capable of handling significantly greater loads.

3.3 Performance Comparison

Early in the design phase, we had outlined the furniture configurations we wanted the system to achieve, as well as performance specifications for the overall system and each individual component (Chapter 2, Table 2.1). Table 3.8 compares the prototype's performance with our requirements.

In summary, we successfully designed a robot that could produce four main target furniture configurations, namely, a chair, a table, a bed and a shelf from it's natural floor configuration. The final height of the chair configurations was 18.75 inches and meets our minimum height specification of 15 inches. similarly the table's final height was 24.25 inches, meeting our minimum height specification of 22.5 inches. Similarly, the final height of the bed configuration and the depth of the shelf configuration of the wall were both 18.75 inches, meeting our initial minimum specification of 16.5 inches and 10 inches respectively.

In terms of load bearing capacity compared with the design specifications, the prototype showed 77% improvement in the floor configuration, 33% and 60% improvement in the table and chair configurations respectively, a 60% improvement in the bed configuration and 400% in the shelf configuration.

Analyzing the total time to reach each configuration, the prototype was 36% faster than expected when configuring into a table, 41% faster when configuring into a chair, 56% faster when configuring into a bed and 43% when configuring into a shelf.

Desired Elements	Min. Height (in)	Height Achieved (in)	Minimum Load Bearing Target (lbs)	Load Bearing Achieved	% Improvement (Load)	Max Config. Time (M:s)	Config. Time Achieved	% Improvement (Time)
Floor	N/A	N/A	300	530	77%	N/A	N/A	
Table	22.5	24.25	300	400	33%	2:00	1:17	36%
Chair	15	18.75	250	400	60%	1:30	0:53	41%
Bed	16.5	18.75	250	400	60%	2:00	0.53	56%
Shelf	10	18.75	20	100	400%	1:30	0.51	43%

Table 3.8: Table comparing the system's performance to design specifications.

Chapter 4

Conclusions and Future Work

In this dissertation, we have presented a new and novel contribution to physically reconfigurable living spaces or 'Robot Rooms'. These Robot Rooms will be capable of actively reconfiguring based on inhabitant needs, in an effort not only to offer practical usability supporting both leisure and productive activities, but also to optimize space.

Specifically, we have successfully conceptualized, designed and prototyped a proof of concept 'Robot Room slice'. Within the slice, robotic elements can change the space from an initial empty floor/wall volume to create chairs, a table, a bed, and a shelf. Collectively, these elements can be combined to provide numerous configurations identified in surveys conducted by our collaborators as being particularly desirable for an adaptive home environment.

The prototype is capable of supporting all seven domestic activities identified in the survey, namely, A) eating dinner with family, B) reading to children, C) watching TV with partner, D) napping, E) taking a video call, f) conducting an online (Zoom) meeting, and H) working on a computer. The resulting prototype is the first physical realization of a Robot Room slice, and establishes the feasibility of engineering the design concept, itself introduced in this dissertation.

We have conducted a series of experiments to evaluate the robotic prototype. The results validate the functionality and performance of the system as designed. Through the course of the research presented in this dissertation we have conceptualized and created a foundational element for robot rooms, proving the concept is feasible, in an effort to pave the way for future researchers to build upon our work to develop the next generation of adaptable spaces.

4.1 Wider Applications of the Research

While the robot we have presented in this work was designed with the urban home setting in mind, the potential applications are not limited to everyday homes. The hospitality industry lends itself to the concept very well, for instance, via dynamic hotel rooms where the room has the ability to dynamically change its layout to cater to diverse guest needs. For instance, a room capable of transforming itself from a workspace during the day to a cozy sleeping area at night, or a room with concealed or expandable beds or storage options may prove highly beneficial. Other hospitality applications might include conference spaces and banquet areas where the layout has to be constantly adjusted due to varying group sizes.

Robot rooms also have potential healthcare applications, in which they can potentially be deployed in emergency rooms and surgery spaces by initially providing a clear and obstruction-free space during patient transportation, with subsequently essential medical furniture such as tables and chairs emerging on demand once a patient is stabilized, saving valuable and critical time. These robots could also be installed in physical rehabilitation and patient rooms, providing reconfigurable layouts tailored to specific patient needs.

In a similar vein, these reconfigurable spaces could be installed in eldercare settings and include features such as height-adjustable dynamic pathways to accommodate wheelchairs and walkers. Shape shifting memory care rooms that can reconfigure with photos and familiar objects, or layouts that can be modify to reflect those that patients with memory loss have lived in, in an effort to stimulate positive memories in dementia patients is another potential application. Similar to banquet spaces and conference rooms, robot rooms in community spaces could change layouts to support group activities based on the number of inhabitants.

In addition, the applications of robot room are not limited to the urban setting. They have the potential to be deployed across a myriad of applications, including but not limited to inhabited air, space, and maritime environments.

4.2 Future work

The work presented in this dissertation resulted in an early prototype demonstrating that the Robot Room slice concept is feasible. Direct extensions of the work presented here could involve: (1) introducing additional panels to the current slice for refined reconfigurability; and (2) the coordination of multiple slices that can work in tandem, extending the scope of the single slice presented here.

The prototype introduced herein was designed to establish the core functionality of the design concept. The design can be further refined, from design perspective and control perspectives. Another area of future refinement is in the ergonomic aspects: specifically user interfaces, as well as comfort and aesthetics for users.

Furthermore, shortly after the completion of this dissertation, a series of user studies will be conducted by our project collaborators at Cornell University, using a corresponding prototype constructed based on the design presented herein. The key goal will be to understand how users would wish to interact with the robot, and learn their preferences. Future versions of the prototype will correspondingly be further refined and developed at Cornell based on user wants and needs, focusing particularly at user interface modalities.

4.2.1 Future Improvements to The Design

While the work presented in this dissertation is novel, it servers a a preliminary proof of concept, with further opportunities for refinement and enhancement. Starting with the track system: albeit rather expensive, custom tracks mimicking those of a roller coaster and a corresponding wheel set can aid in smoother panel traversal. Similarly, use of high-angle conveyor or vertical sidewall conveyor belts could serve as an alternative to the winch used in this design, though they would have to be custom designed to fit a small form factor and would be considerably more expensive.

In terms of the control system, future researchers can embed wireless communication into the system and develop a dedicated mobile application to allow user control via their phones and the internet. The system can also be embedded with various sensors and cameras to enable vision-based gesture control. In a future build where the slice is expanded to have a second set of vertical tracks, a second winch can be added to the system and a feedback based control system can be implemented to control the winches and the panels from the user interface, eliminating the need for a separate remote to operate the winch.

When it comes to material selections, the steel used throughout the prototype described herein can potentially be replaced with aluminum or other lighter metals in an effort to reduce the overall weight. However, this could potentially have an adverse effect on the overall load bearing capacity of the system. In terms of actuators, the electrical based linear actuators in the system can potentially be replaced with hydraulic actuators which are better suited for high force applications. However, related drawbacks include that non electric-based actuators generally do not offer great flexibility in terms of controls, and are generally slower.

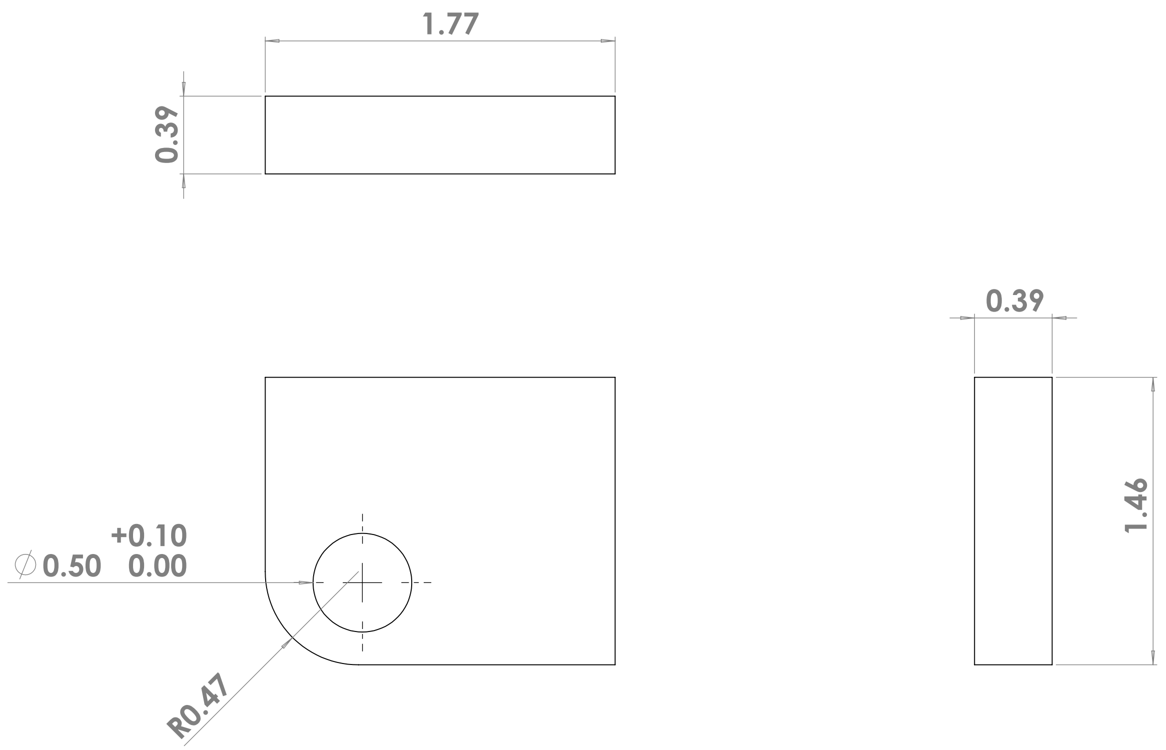
Considering the ergonomics, a viable next step could be adding retractable back supports for the chairs and hidden cushioned seating that can rotate into place once the chairs actuate. Similarly in the shelf configuration, in the current prototype the user is handed a custom-made wooden plank that gets placed on the actuated panel to act as the surface of the self. Embedding a 'surface' within the system which is capable of collapsing and expanding with the panels is a potential avenue for future exploration. Embedding such a surface on all four sides of every panel can also help hide the electronics and the inner mechanisms such as the scissor arms which would be beneficial from an ergonomics perspective. Future researchers can also approach and explore ergonomics quantitatively, by defining what the work space is, the volume of space the robot occupies, and how it can be improved upon from an ergonomics point of view. Researchers can also explore adjustable seating, and in turn measure and the load bearing performances at different actuation heights, to enable support and fit a variety of body types.

Acknowledgments

This work was supported in part by NSF grant 2221126.

Appendices

Appendix A Models and Dimensions of Major Components of The Panels and Carriage System



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
LINEAR TOLERANCES: ± 0.05IN

DEBURR AND BREAK SHARP EDGES

REVISION

COUNT: 8x

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL: Steel

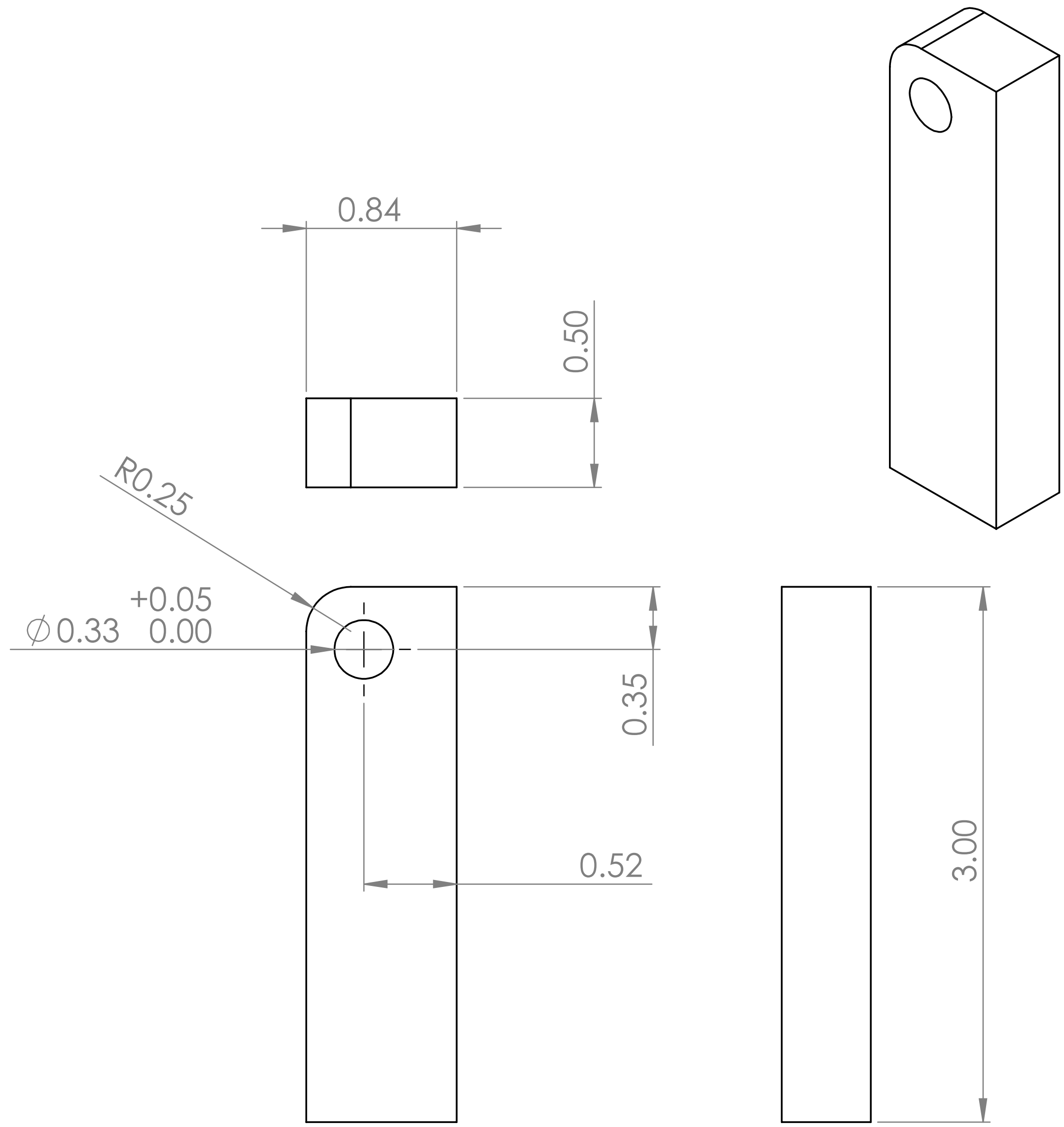
DWG NO. Drawing_Scissior_Arm_MB

A3

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
LINEAR TOLERANCES: ± 0.05IN

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

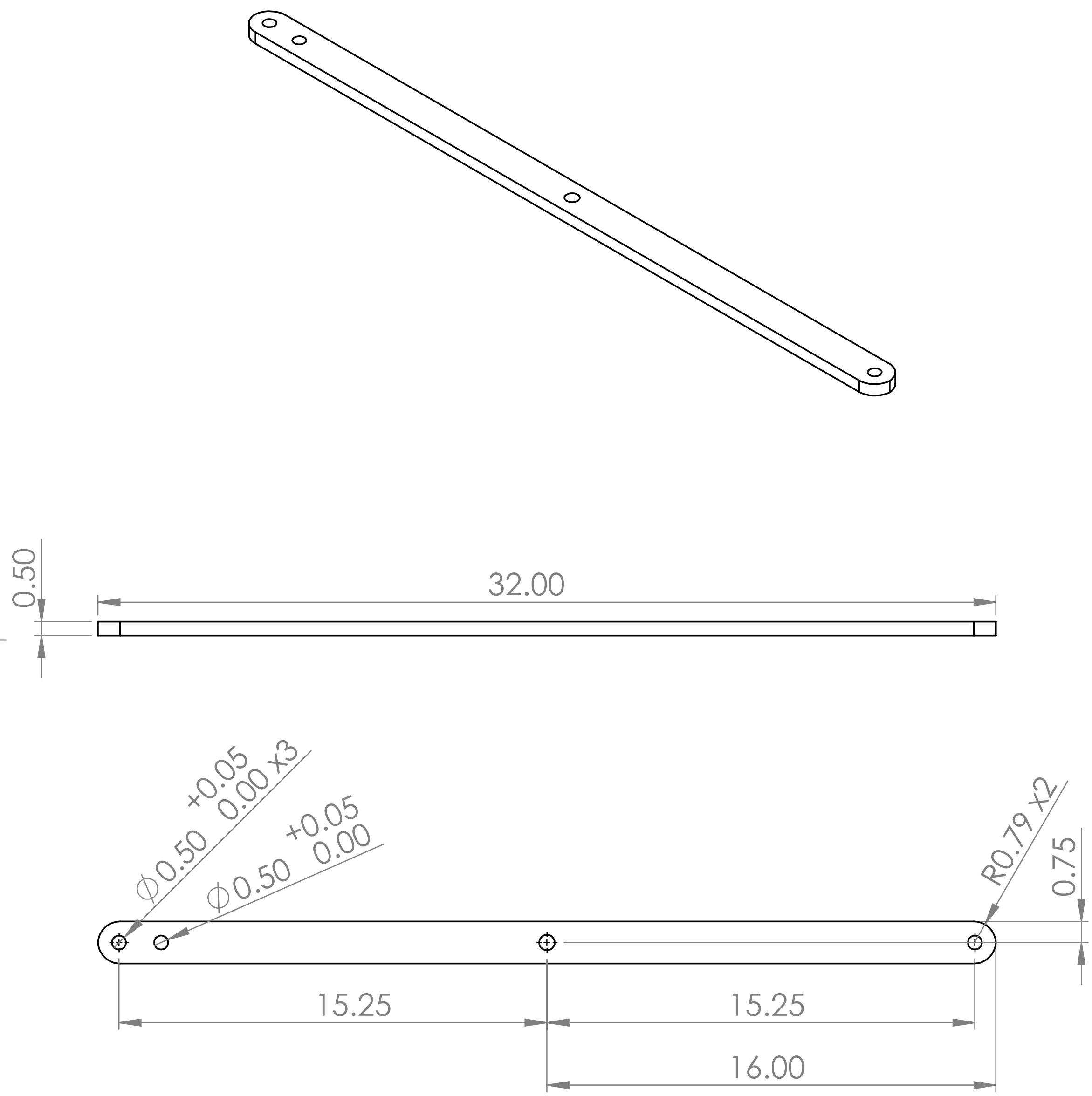
Actuator_Rear_Mounting_Bracke

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
LINEAR TOLERANCES: ± 0.05IN

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

WEIGHT:

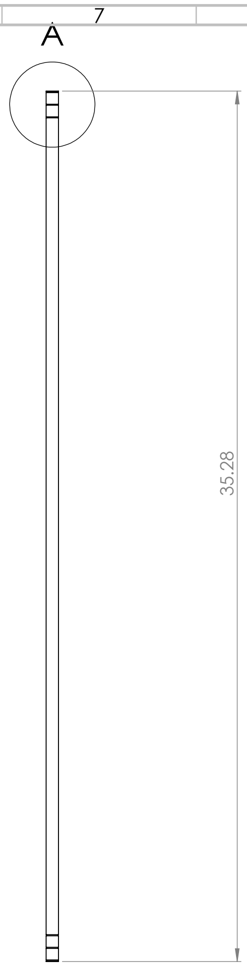
DWG NO.

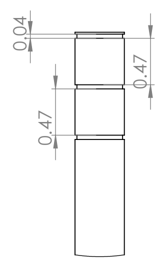
Scissior_Arm

A4

SCALE:1:6

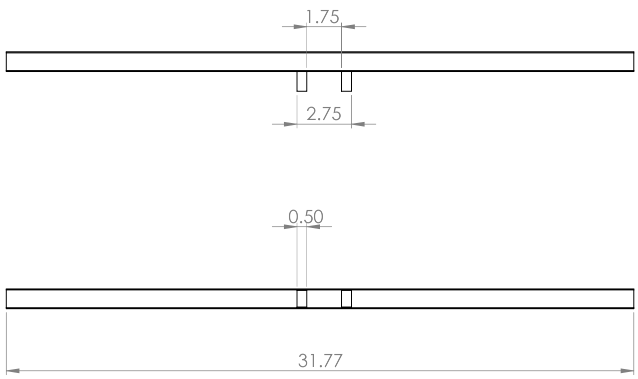
SHEET 1 OF 1

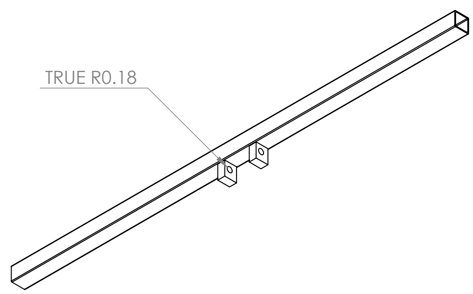




DETAIL A
SCALE 1 : 1

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:			FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE				TITLE:	
DRAWN								
CHK'D								
APPV'D								
MFG								
Q.A				MATERIAL:			DWG NO. WheelAxle	A3
				WEIGHT:			SCALE:1:10	SHEET 1 OF 1





Actuator Head Mounting Bracket

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

A3

WEIGHT:

SCALE:1:5

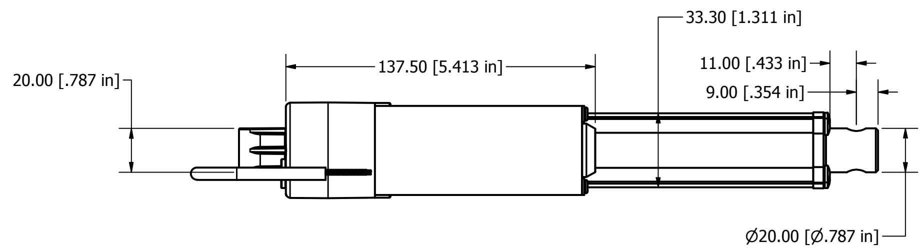
SHEET 1 OF 1

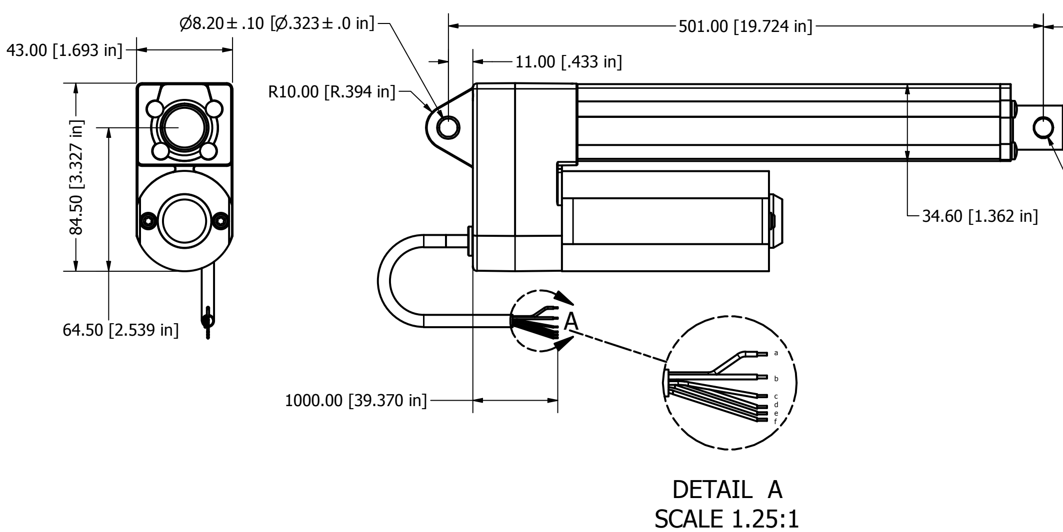
F-SD-H-450-12v-14
FORCE: 450Lbs (2000N)

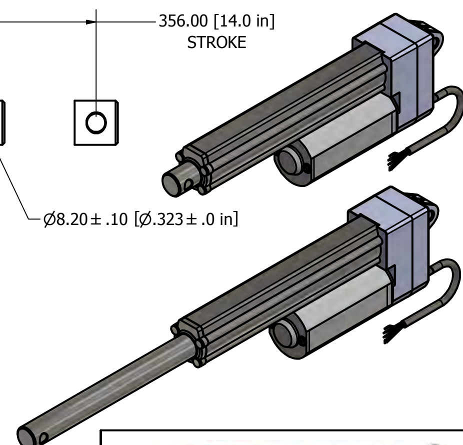
Actuator Wiring		
Color	Brown	Blue
Extend	-	+
Retract	+	-

TABLE		
NO.	Item	Detail
1	Model No.	F-SD-H-220-12v-14"
2	Stroke	356±3mm [14 in]
3	Installation size	501±3mm [19.724 in]
4	Voltage	12V DC
5	Free load speed	6mm/s±10%
6	Dynamic load capacity	450Lbs (2000N)
7	Cable thinkness	Six-cores wire
8	Cable length	1000±10%mm [39.370 in]
9	Wire connector	tinned bare wires
10	Front mounting end	Ø8.2mm [Ø.323 in]
11	Rear mounting end	Ø8.2mm [Ø.323 in]
12	Limited switches	Built-in,unadjustable
13	Protection Rate	IP66
	Pulse/mm (single hall)	41.1 pulse/mm

Wiring For Hall Sensor			
c	Red	26AWG	V+(5~15V MAX)
d	Yellow	26AWG	Hall1
e	White	26AWG	Hall2
f	Black	26AWG	V







FIRGELLI AUTOMATIONS ©

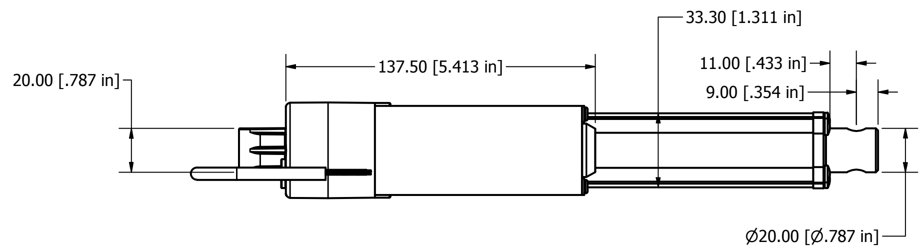
SIZE	DWG NO	REV
A3	F-SD-H-450-12v-14	
SCALE 1 / 1.75	SHEET 1 OF 1	

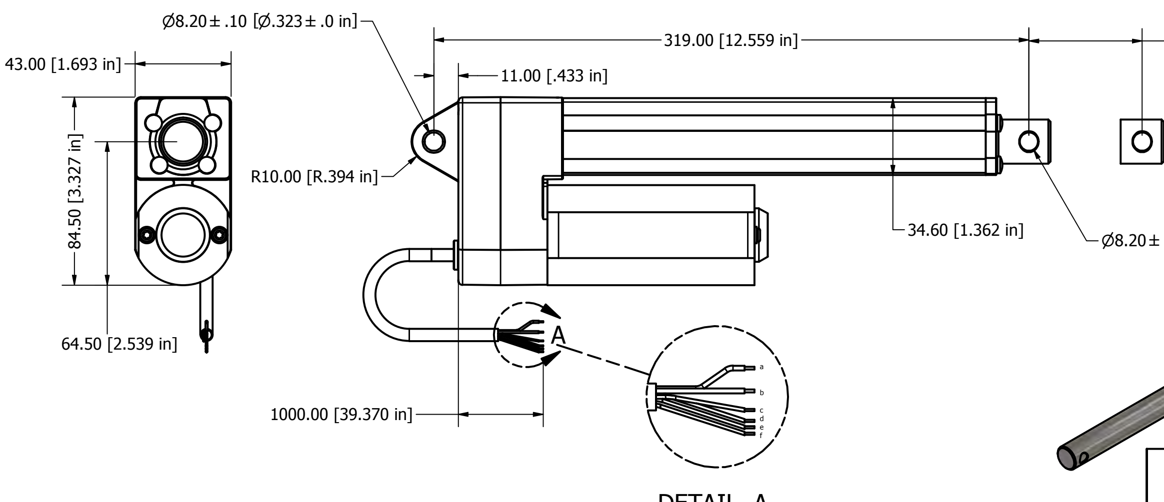
F-SD-H-450-12v-8
FORCE: 450Lbs (2000N)

Actuator Wiring		
Color	Brown	Blue
Extend	-	+
Retract	+	-

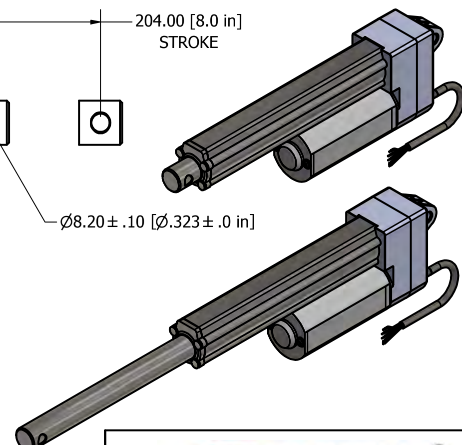
TABLE		
NO.	Item	Detail
1	Model No.	F-SD-H-450-12v-8"
2	Stroke	204±3mm [8 in]
3	Installation size	319±3mm [12.559 in]
4	Voltage	12V DC
5	Free load speed	6mm/s±10%
6	Dynamic load capacity	450Lbs (2000N)
7	Cable thinkness	Six-cores wire
8	Cable length	1000±10%mm [39.370 in]
9	Wire connector	tinned bare wires
10	Front mounting end	Ø8.2mm [Ø.323 in]
11	Rear mounting end	Ø8.2mm [Ø.323 in]
12	Limited switches	Built-in,unadjustable
13	Protection Rate	IP66
	Pulse/mm (single hall)	41.1 pulse/mm

Wiring For Hall Sensor			
c	Red	26AWG	V+(5~15V MAX)
d	Yellow	26AWG	Hall1
e	White	26AWG	Hall2
f	Black	26AWG	V



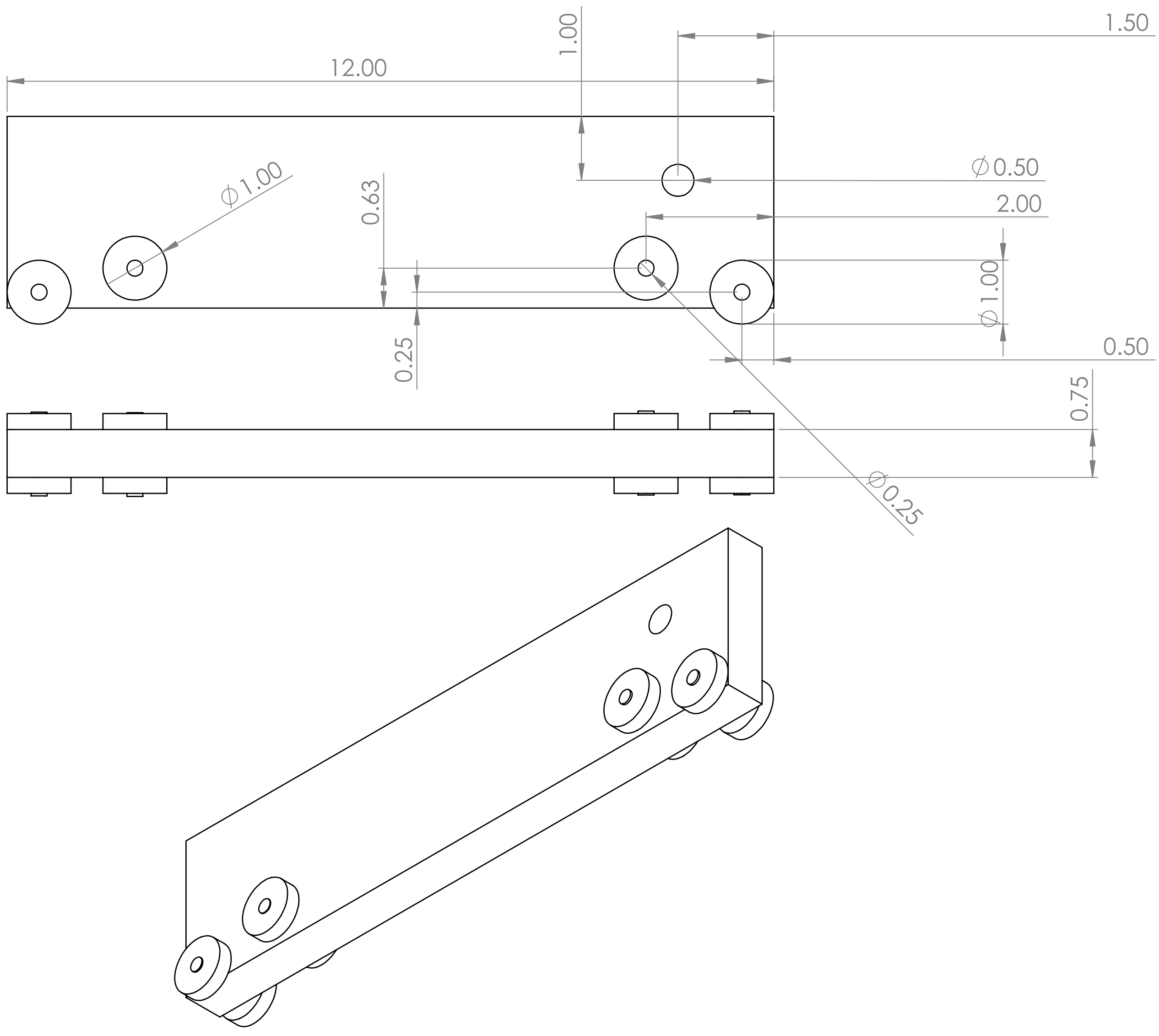


DETAIL A
SCALE 1.25:1



FIRGELLI AUTOMATIONS

SIZE	DWG NO	REV
A3	F-SD-H-450-12v-8	
SCALE 1 / 1.75	SHEET 1 OF 1	


12.00
1.00
1.50
Ø1.00
0.63
Ø0.50
2.00
Ø1.00
0.25
0.50
0.75
Ø0.25

Appendix B Arduino Code For System Control

```
// === Actuator Configuration ===
#define TOLERANCE 100
#define PULSES_PER_INCH_A2 4185.7 // pulses per inch for actuator 2

// Actuator 1 (8")
#define A1_HALL1 2
#define A1_HALL2 3
#define A1_RPWM 5
#define A1_LPWM 6
#define A1_REN 7
#define A1_LEN 8

// Actuator 2 (14")
#define A2_HALL1 18
#define A2_HALL2 19
#define A2_RPWM 9
#define A2_LPWM 10
#define A2_REN 11
#define A2_LEN 12

// Actuator 3 (8")
#define A3_HALL1 20
#define A3_HALL2 21
#define A3_RPWM 22
#define A3_LPWM 23
#define A3_REN 24
#define A3_LEN 25

// === Encoder Variables ===
```

```
volatile long encoder1 = 0;
volatile long encoder2 = 0;
volatile long encoder3 = 0;
int lastEncoded1 = 0, lastEncoded2 = 0, lastEncoded3 = 0;

// Logical Zero Positions
long A1_LOGICAL_ZERO = 0;
long A2_LOGICAL_ZERO = 0;
long A3_LOGICAL_ZERO = 0;

// Targets
long target1 = 0, target2 = 0, target3 = 0;
bool go1 = false, go2 = false, go3 = false;

void setupActuatorPins(int rpwm, int lpwm, int ren, int len) {
  pinMode(rpwm, OUTPUT);
  pinMode(lpwm, OUTPUT);
  pinMode(ren, OUTPUT);
  pinMode(len, OUTPUT);
  digitalWrite(ren, HIGH);
  digitalWrite(len, HIGH);
}

void setup() {
  Serial.begin(9600);

  setupActuatorPins(A1_RPWM, A1_LPWM, A1_REN, A1_LEN);
  setupActuatorPins(A2_RPWM, A2_LPWM, A2_REN, A2_LEN);
  setupActuatorPins(A3_RPWM, A3_LPWM, A3_REN, A3_LEN);
```

```
  pinMode(A1_HALL1, INPUT); pinMode(A1_HALL2, INPUT);
  pinMode(A2_HALL1, INPUT); pinMode(A2_HALL2, INPUT);
  pinMode(A3_HALL1, INPUT); pinMode(A3_HALL2, INPUT);

  attachInterrupt(digitalPinToInterrupt(A1_HALL1), updateEncoder1, CHANGE);
  attachInterrupt(digitalPinToInterrupt(A1_HALL2), updateEncoder1, CHANGE);
  attachInterrupt(digitalPinToInterrupt(A2_HALL1), updateEncoder2, CHANGE);
  attachInterrupt(digitalPinToInterrupt(A2_HALL2), updateEncoder2, CHANGE);
  attachInterrupt(digitalPinToInterrupt(A3_HALL1), updateEncoder3, CHANGE);
  attachInterrupt(digitalPinToInterrupt(A3_HALL2), updateEncoder3, CHANGE);

  delay(200); // Allow encoder values to settle

  A1_LOGICAL_ZERO = encoder1;
  A2_LOGICAL_ZERO = encoder2;
  A3_LOGICAL_ZERO = encoder3;

  encoder1 = 0;
  encoder2 = 0;
  encoder3 = 0;

  Serial.println("System Ready. Logical zeros captured.");
}

void loop() {
  handleSerial();

  handleActuatorToLogicalZero(encoder1, target1, A1_RPWM, A1_LPWM, go1);
  handleActuatorToLogicalZero(encoder2, target2, A2_RPWM, A2_LPWM, go2);
  handleActuatorToLogicalZero(encoder3, target3, A3_RPWM, A3_LPWM, go3);
```

```
  Serial.print("E1:␣"); Serial.print(encoder1); Serial.print("␣T1:␣"); Serial.
      ↪ print(target1);
  Serial.print("␣|␣E2:␣"); Serial.print(encoder2); Serial.print("␣T2:␣"); Serial.
      ↪ print(target2);
  Serial.print("␣|␣E3:␣"); Serial.print(encoder3); Serial.print("␣T3:␣"); Serial.
      ↪ println(target3);

  delay(100);
}

void handleSerial() {
  if (Serial.available()) {
    String input = Serial.readStringUntil('\n');
    input.trim();

    if (input == "c1") { analogWrite(A1_RPWM, 255); analogWrite(A1_LPWM, 0); }
    else if (input == "c2") { analogWrite(A2_RPWM, 255); analogWrite(A2_LPWM, 0);
        ↪ }
    else if (input == "c3") { analogWrite(A3_RPWM, 255); analogWrite(A3_LPWM, 0);
        ↪ }
    else if (input == "h") {
      target1 = A1_LOGICAL_ZERO;
      target2 = A2_LOGICAL_ZERO;
      target3 = A3_LOGICAL_ZERO;
      go1 = go2 = go3 = true;
    }
    else if (input == "pc2") {
      long retractAmount = (long)(4.25 * PULSES_PER_INCH_A2);
      target2 = -retractAmount;
```

```
      go2 = true;
      Serial.println("Partial retract actuator 2 by 4.75 inches.");
    }
    else if (input == "s") {
      stopAllActuators();
      go1 = go2 = go3 = false;
      Serial.println("Emergency Stop: All actuators stopped.");
    }
  }
}

void handleActuatorToLogicalZero(volatile long &pos, long &target, int rpwm, int lpwm, bool &go) {
  if (!go) return;
  long error = target - pos;

  if (abs(error) <= TOLERANCE) {
    analogWrite(rpwm, 0);
    analogWrite(lpwm, 0);
    go = false;
    Serial.println("Target (logical zero or partial) reached.");
  } else if (error < 0) {
    analogWrite(rpwm, 255); analogWrite(lpwm, 0); // Retract
  } else {
    analogWrite(rpwm, 0); analogWrite(lpwm, 255); // Extend
  }
}

void stopAllActuators() {
  analogWrite(A1_RPWM, 0); analogWrite(A1_LPWM, 0);
```

```
  analogWrite(A2_RPWM, 0); analogWrite(A2_LPWM, 0);
  analogWrite(A3_RPWM, 0); analogWrite(A3_LPWM, 0);
}

// === Encoder ISRs ===
void updateEncoder1() {
  int MSB = digitalRead(A1_HALL1);
  int LSB = digitalRead(A1_HALL2);
  int encoded = (MSB << 1) | LSB;
  int sum = (lastEncoded1 << 2) | encoded;
  if (sum == 0b1101 || sum == 0b0100 || sum == 0b0010 || sum == 0b1011) encoder1
      ↪ --;
  else if (sum == 0b1110 || sum == 0b0111 || sum == 0b0001 || sum == 0b1000)
      ↪ encoder1++;
  lastEncoded1 = encoded;
}

void updateEncoder2() {
  int MSB = digitalRead(A2_HALL1);
  int LSB = digitalRead(A2_HALL2);
  int encoded = (MSB << 1) | LSB;
  int sum = (lastEncoded2 << 2) | encoded;
  if (sum == 0b1101 || sum == 0b0100 || sum == 0b0010 || sum == 0b1011) encoder2
      ↪ --;
  else if (sum == 0b1110 || sum == 0b0111 || sum == 0b0001 || sum == 0b1000)
      ↪ encoder2++;
  lastEncoded2 = encoded;
}

void updateEncoder3() {
```

```
  int MSB = digitalRead(A3_HALL1);
  int LSB = digitalRead(A3_HALL2);
  int encoded = (MSB << 1) | LSB;
  int sum = (lastEncoded3 << 2) | encoded;
  if (sum == 0b1101 || sum == 0b0100 || sum == 0b0010 || sum == 0b1011) encoder3
      ↪ --;
  else if (sum == 0b1110 || sum == 0b0111 || sum == 0b0001 || sum == 0b1000)
      ↪ encoder3++;
  lastEncoded3 = encoded;
}
```

Appendix C Python Code For Graphical User Interface (GUI)

```
import tkinter as tk
from tkinter import messagebox
import serial
import time

# Attempt Serial Connection (non-blocking for GUI testing)
try:
    ser = serial.Serial('COM3', 9600, timeout=1)
    time.sleep(2)
    serial_available = True
except serial.SerialException:
    serial_available = False
    print("Warning: COM3 not found. GUI will run in demo mode.")

# Send command to Arduino or log if in demo mode
def send_command(cmd):
    if serial_available:
        ser.write(cmd.encode())
        print(f"Sent: {cmd}")
    else:
        print(f"[Demo Mode] Would send: {cmd}")

# Special Bed command: retract actuator 3 fully, then retract actuator 2 partially
def bed_command():
    send_command("c3")
    root.after(3000, lambda: send_command("pc2")) # Delay 3000 ms before sending
        ↪ second command
```

```
# Create GUI Window
root = tk.Tk()
root.title("Robot␣Room␣Control␣Interface")
root.geometry("850x400")
root.configure(bg="#0F4C75") # Deep teal-blue background

# Title
title_label = tk.Label(
    root, text="Robot␣Room␣Control␣Interface",
    font=("Helvetica", 22, "bold"),
    bg="#0F4C75", fg="white"
)
title_label.pack(pady=20)

# Button Styling
button_style = {
    "bg": "white", # White button
    "fg": "#0077B6", # Teal-blue text
    "activebackground": "#E0F7FA", # Light blue on click
    "activeforeground": "#0077B6",
    "font": ("Helvetica", 12, "bold"),
    "width": 18,
    "height": 2,
    "bd": 3,
    "relief": "raised"
}

# Button Frame (2 rows)
button_frame = tk.Frame(root, bg="#0F4C75")
button_frame.pack()
```

```
# First row
row1 = tk.Frame(button_frame, bg="#0F4C75")
row1.pack(pady=10)

tk.Button(row1, text="Chair␣1", command=lambda: send_command("c1"), **button_style
    ↪ ).pack(side="left", padx=10)
tk.Button(row1, text="Chair␣2", command=lambda: send_command("c3"), **button_style
    ↪ ).pack(side="left", padx=10)
tk.Button(row1, text="Table", command=lambda: send_command("c2"), **button_style).
    ↪ pack(side="left", padx=10)
tk.Button(row1, text="Bed", command=bed_command, **button_style).pack(side="left",
    ↪  padx=10)

# Second row
row2 = tk.Frame(button_frame, bg="#0F4C75")
row2.pack(pady=10)

tk.Button(row2, text="Shelf", command=lambda: send_command("c3"), **button_style).
    ↪ pack(side="left", padx=10)
tk.Button(row2, text="Home", command=lambda: send_command("h"), **button_style).
    ↪ pack(side="left", padx=10)
tk.Button(row2, text="Emergency␣Stop", command=lambda: send_command("s"), **
    ↪ button_style).pack(side="left", padx=10)

# Run the GUI
root.mainloop()
```

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