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The Networked, Robotic *home*+ Furniture Suite: a Distributed, Assistive Technology Facilitating Aging in Place*

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Abstract— **We introduce and detail a novel, networked and interoperative suite of robotic furniture. This suite forms a key part of our development of *home*+, an assistive technology environment aimed at supporting aging in place. This paper elaborates the design and construction process for the three robotic furniture core elements of *home*+: a chair, featuring gesture-controlled assistive lift; a morphing side table; and an adaptive screen. The sensor suite, networking, and user interface for the system is described and discussed. We report on initial experiments with senior citizens using the system.**

I. Introduction

Overwhelmingly, people want to grow older living in their own homes. According to research by the American Association of Retired Persons (AARP), nearly 90 percent of seniors want to stay in their own homes as they age [3],[19], a phenomenon characterized as aging in place. Aging in place describes individuals choosing to remain in their own homes, independently, for as long as possible, rather than living in institutionalized settings [4],[6],[14],[17],[22],[23],[24].

Despite an overwhelming preference to live at home [3],[19], and a surprising receptiveness to new technologies in the home [7],[10],[13],[27], many people with reduced mobility, temporarily or indefinitely, are resigned to live in costly care facilities staffed with costly and overextended healthcare staff [16]. Moreover, with the dramatic, demographic shift to an older population, there is a smaller segment of the population to care for and pay for the wellbeing of older and clinical populations. This places strain on healthcare and family support systems.

At the same time, homes—even homes built on a one-size-fits-all, "universal design" approach—remain essentially conventional, low-tech, and maladaptive to dramatic life changes. Inside homes, technology supporting health and wellbeing is manifested not as the physical fabric of the house interior and its various furnishings, but instead as primarily software systems. Such software technology is frequently grouped into three areas: (1) those supporting daily tasks and routines, (2) those recognizing and assisting with crisis, and (3) those supporting the peace of mind of adult children or caretakers in order to facilitate independence, safety, and quality of life [14]. Telemedicine, e-health, and computerized monitoring devices—home-wide and wearable, are a few examples for home application [7]; but even cross-disciplinary efforts like the Aware Home of Georgia Tech [2] remain fundamentally software-based.

As for the possibility of an in-home "humanoid" service robot, data suggests that many people want service robots to simply help them compensate for their reduced capacities, which doesn't necessitate assistive robots physically resembling humans or exhibiting human traits such as creative thinking, judgment, or friendship [26]. Robotics research for health and eldercare applications has tended to focus either on specialized devices aimed at dedicated tasks (e.g. rehabilitation robotics, robot-assisted surgery, prosthetics) or as replacements for humans engaged in healthcare-related activity [20],[21] or as companions.

The efforts just mentioned—universal design of "adaptable" housing, specific applications of software systems, and humanoid robot assistants—all promise to contribute to the quality of longer-lived lives; but the reality is not so sweet. Designed from the outset to accommodate "everyone" through such means as a no-step entry, wide doorways, and "extra space" for maneuverability [1], universally designed homes are constrained to accommodate "everyone," and often need some manual reconfiguring by professional builders at the instant when the needy inhabitant is most unprepared to see through and pay for such home remodeling activity; the recourse is to move the inhabitant from his or her home into assisted care. A wearable or home-wide monitoring device is capable of registering a problem with the inhabitant but offers no immediate solution—maybe only a signal to move the inhabitant from his or her home into assisted care. Finally, a humanoid assistant that exhibits wide-ranging abilities has yet to be realized, and will likely come with safety, privacy, and other ethical concerns, and a prohibitive retail price. For now, the bigger picture is one of an older person—a wearable monitoring device strapped around her wrist—confined to a home that she can't easily adapt, keeping company with a machine that looks something like her (or her pet), but lacks a capacity to feel and understand as she (or even her pet) does.

Distinct from previous work in the universal design of adaptable housing, specific applications of software systems, and humanoid assistants and companionable pets, our approach to aging in place—at the interface of architecture, robotics, human factors psychology, and medicine—seeks a response to fundamental questions:

How can homes be outfitted with intelligent hardware enabling independent living?

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And, if such a thing were constructed, would it be usable by seniors and useful for aging in place?

Joined by medical staff at the Roger C. Peace Rehabilitation Hospital of the Greenville, South Carolina Health System (GHS) [25], our trans-disciplinary research team focuses its response on the development of a distributed, architectural robotic ([9]) environment that we call *home+*, an intelligent and interoperable suite of robotic home furnishings. These furnishings might take the form of seating, storage, lighting, coatracks, and ceiling-mounted (fetching) robots, likely operating as hybrids of these. Our broader aim for *home+* is to increase the quality of life for individuals with impaired mobility and cognitive functioning by enabling them to maintain living within their own homes.

The vision of such an intelligent, robotic, home environment is not only ours. For one, KAIST's "Intelligent Sweet Home" shares our vision of embedding a suite of robotics in the home; but the only robotic component receiving significant attention, to our knowledge, is a robotic hoist for transferring a user to and from bed [18]. The other envisioned components of the Intelligent Sweet Home can be grouped together with like efforts for singular home components that adapt either "off the shelf" robotic arms (attached to wheelchairs or ceilings) or mobile robots for mostly fetch-and-carry scenarios [5],[8],[11],[12],[15]. While KAIST's effort does not explicitly concern robotic furniture, we nevertheless recognize its vision as complementary to our own and converging with software-focused efforts to realize the ambition of an enabling, cyber-physical, home environment. Diverging from efforts by KAIST and others, we envision home+ unassertively "aging in place" with those living with it.

In earlier work, our research team and partners developed a discrete component of *home+*: the Assistive, Robotic Table (ART) (figure 1). However, the team persists in developing the larger *home+* concept, recognizing ART not as an isolated artifact but as integral to a larger, assistive and enabling, cyber-physical ecosystem—*home+*. We envision this ecosystem ultimately including not only robotic furniture, as discussed in this paper, but also artifacts of the kinds just considered—universal design, software systems, and humanoid assistants—as well as digital appliances, sensor networks, and related artifacts comprising an internet of things (IoT). For the growing numbers of people wishing to age in place, this expanded picture promises to be far brighter, as we are accustomed to sharing our homes with furniture for much of human history. Long integral with our lifestyle and living spaces, furniture is an opportune platform for enabling independence and the anchoring of other types of assistive technologies.

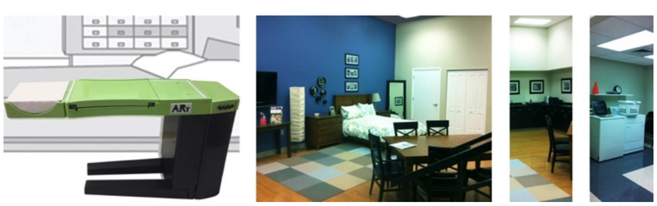

Figure 1. Left: Assistive Robotic Table (ART). Center and right images: the home+ environment in the Greenville Hospital System.

Overall, *home+* benefits from the convergence of advanced architectural design, computing, and robotics largely absent from prior efforts in assistive technologies. In particular, this enabling technology is not distributed everywhere in the physical environment but where it's needed; it is not intended to be invisible (as in ubiquitous computing) but rather, by design, visible and attractive to the inhabitant and integral to the home; and it is not meant to serve as a means for surveillance or as a replacement for companionship, but as a welcoming form of environmental support that dignifies people and recognizes what people can do for themselves.

In this paper, we introduce a suite of robotic furniture elements designed for *home+*. The basic design and functionality of the three elements are described in the following section. Section III discusses the associated sensor suite and element communication. Initial experiments with the elements featuring senior citizens are reviewed in section IV. Conclusions are presented in section V.

II. HOME+ ROBOTIC FURNITURE ELEMENTS

The home+ furniture suite consists of three interoperable elements: chair, side table, and screen (figure 2). All elements are sheathed in alucobond (easily foldable metallic sheet) material. The design and physical realization of each of these elements is decreibed in the following subsections.

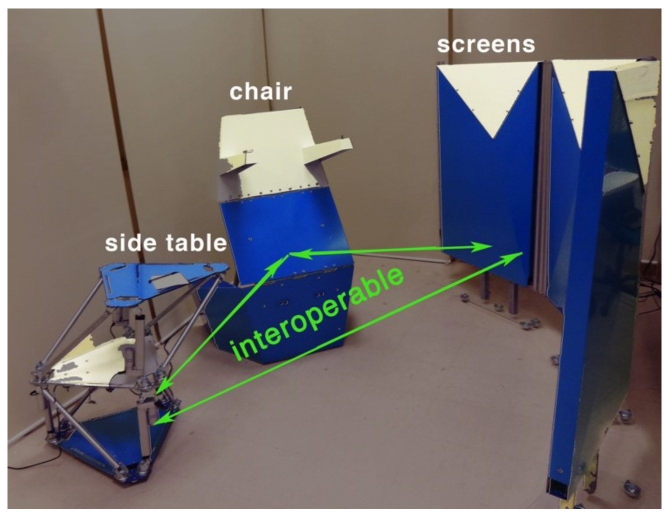

Figure 2. The home+ furniture suite.

A. Chair

The fundamental purpose of the chair is to assist persons with limited mobility to sit or stand with reduced pressure on their joints. While the concept of a chair assisting a person to stand is not novel [28], the chair in this project is also intended to serve as a central controller for the three individual components.

The original design for the chair envisioned exploitation of the load bearing capabilities of triangles, in order to distribute the weight of a sitting or standing person and the utilization of linear actuators to move the chair from sitting to standing position and back to sitting position. After several design iterations, the ultimate realization of the chair varied from the original triangle based design concept. Instead, the static load bearing structure was a rectangular frame built from extruded aluminum bars (figure 3, left). Two linear actuators aligned along the diagonal bars from back to front bear the dynamic load of the chair and user while in the standing position. They were aligned within a truss pattern that constrained the back of the chair to remain upright and distributed the load forces to the aluminum frame (figure 3).

The rectangular design resulted in a stronger chair than feasible with the original design concept based on triangles. The design allowed the user to place all their weight upon the armrests while the chair is in motion, and to lean against the chair without fear of falling or slipping. Once seated, the individual can manipulate the remaining two elements of the system via controls (section III) on the armrest.

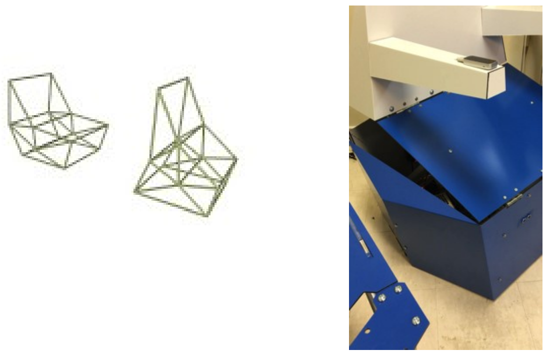

Figure 3. Left: underlying structural framework for chair, in lowered and raised configurations. Right: physical realization of chair, in patially raised configuration. Note user controls on armrest.

B. *Side Table*

The key objective for the table was to provide a surface which can support a wide range of different user activities by changing the table height. Conceptually, the table can act as a side table where a user can leave their coffee cup while reading, a working desk where they rest their computer on to write, or a podium supporting their I-pad while they are standing and talking to a client.

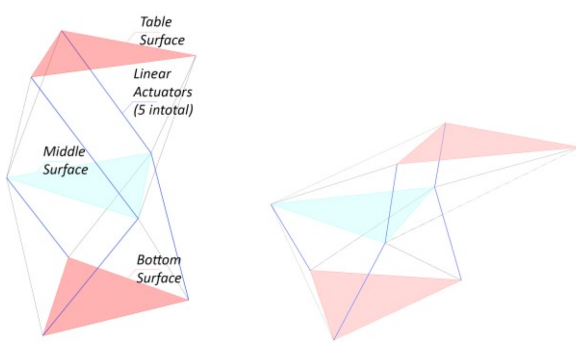

Figure 4. Two-stage parallel mechanism design concept for table. Three horizontal surfaces (top, bottom, middle) are translated and rotated with respect to the vertical axis by changing the lengths of two of the intermediate legs using linear actuators.

The key design goals were to realize the height variation using elegant and appealing geometrical motion, achieved via a simple mechanism. The design was realized by a two-stage parallel mechanism connecting equilateral triangles at base, tabletop, and in the middle of the table (figure 4.). The transforming of the table shape is effected purely by the mechanism of linear actuators.

Implementing two legs with linear actuators, the table can realize a significant height variation while simultaneously rotating the triangle at the top of each stage. As this shape transformation realizes two coupled degrees of freedom, (height variation and rotation about the vertical axis), table geometry is non-linear. Ball joints are used at the vertices of the triangles to realize the non-linear transformation.

Figure 5. Table from below showing detail of linear actuator arrangment.

The table was controlled wirelessly by the user from the chair (section III). The design is robust, producing smooth and fast movement. The triangulated structure frames proved to be strong and stable. The height variations (26 inches to 37 inches, minimum to maximum tabletop height above floor) achieved by the robotic system were deemed to be sufficient to support the different user activities (section IV).

C. *Screen*

The screen element is a flexible, adaptable and reconfigurable partition. The design goals was to create different spatial configurations that suggest and support alternative activities within a single space. Ultimately, we visualize the partition as providing physical support for a TV, bookshelves and other components that are commonly installed on walls of conventional homes. The wider vision for the screen is for its panels to transform the space while supporting the elder user in various activities within their home environment.

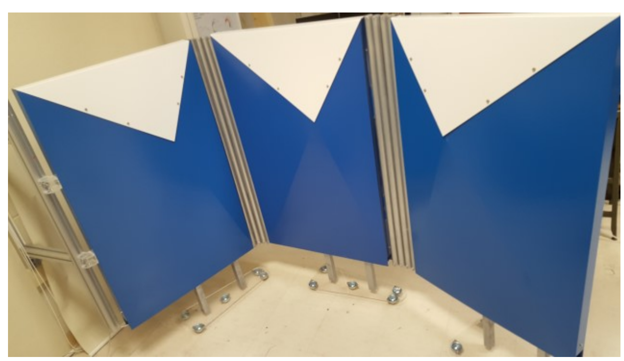

Figure 6. Screen featuring three independently movable panels. Actuation is via internal tendons driven by internally mounted electric motors.

The physical realization of the partition resulted in a modular system composed of three elements - panels, hinges and actuators. The panels were constructed from wood frame covered by alucobond sheeting. Each panel was mounted on a laser cut translucent acrylic horizontal base, which rolls on four ball-bearing casters (figure 6). The tube hinges were composed of four PVC tubes attached by a flexible cable. As illustrated in figure 7, two stepper motors are housed inside the (blue) alucobond casing. These motors actuate pre-tensioned tendons which terminate in the next panel in the chain. Actuation of the tendons effect bending in each four tube hinge, ultimately determining the screen shape.

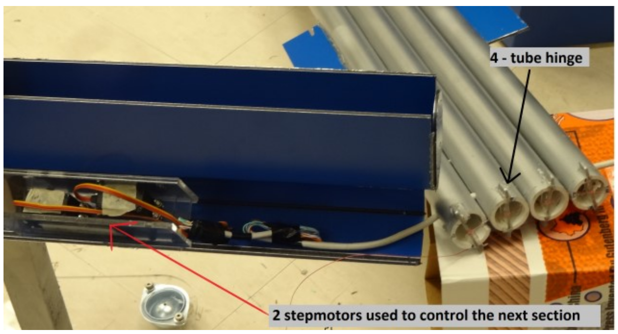

Figure 7. Detail of screen panel hinge, showing embedded stepper actuator and four-tube hinge design, used to enable deployment of screen into folded configuration.

The four tube hinge design produced a rounded rather than angled panel connection, allowing the panels to fold back on each other when one of the tendons are activated by the step motor. As this is a modular system, it is possible to assemble as many panels as needed to satisfy the space configuration required.

III. THE HOME+ SUITE ENSEMBLE

A. *Sensing Mode*

There are two modes within which the overall system operates, idle mode and interactive mode. The modes are alternated between by a button located in the right armrest of the chair. The system is in idle mode when the chair is unoccupied and waiting for the user to approach the chair to sit. Interactive mode occurs when the chair is occupied and allows the seated individual to control the table or screen as they wish.

In idle mode, the system constantly scans the area directly in front of the chair in order to detect if someone is waiting to sit or stand. The sensing for this is achieved using two ultrasonic distance sensors embedded in the front plate of the chair. If both sensors detect a stationary object, then the chair rises to meet the person or raises them to standing position. If one or both sensors do not detect an object within a set range, then the chair lowers to sitting position until needed.

In interactive mode, the chair assumes it is occupied. Now the seated individual is capable of controlling either the table or the screen (figure 8) using devices embedded in each armrest. The chair operates as the control element but does not directly actuate or interact with the other elements except to provide auxiliary feedback to the individual as they manipulate the other elements.

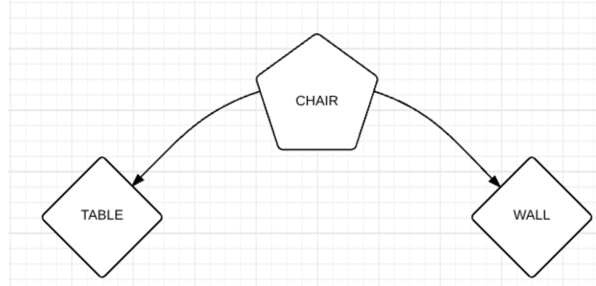

Figure 8. The chair forms the central element in the communications for the suite allowing the user to command the table and screen (wall).

B. *Communications and Software*

The *home+* suite is connected via a network of Xbee 802.15.4 PRO RF Modules [29]. The Xbee-PRO is ideal for use in *home+* since it allows multipoint broadcasting. Each element of the *home+* system contains an Xbee-PRO module and an Arduino. The chair acts as the central hub of *home+* and features a PC in the loop that is directly attached to the Xbee module. The PC is connected to a Leap motion controller – enabling gesture-based user inputs - and Xbee via serial port (figure 9). A java program runs on the PC that reads the data from the leap motion and generates a unique bytecode that is broadcast to either the table or wall depending on the leap operating mode. The table and wall Xbee devices currently only receive information but have the capability to both send and receive. This functionality will be necessary for the implementation of additional features.

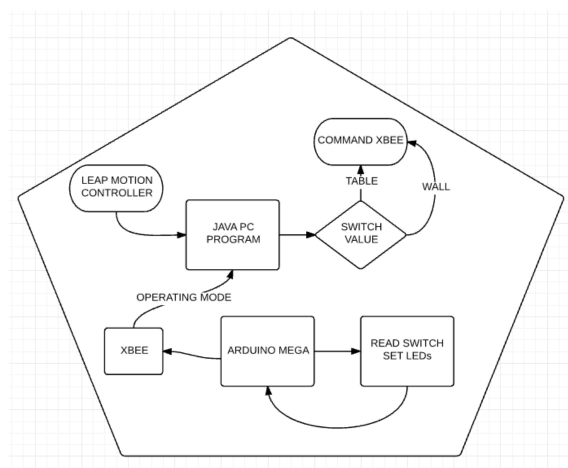

Figure 9. Connectivity within suite ensemble communications system.

C. *User Interface*

The user interface is built into the chair arm rests (figure 10). The LED array consists of two groups of LEDs. The first group represents whether the user is controlling the table – blue, the table – green, or nothing at all. The leap operating mode can be changed by the three way switch. This second mode indicates what section (panel) of the wall the user is controlling base – yellow, middle – orange, end – red.

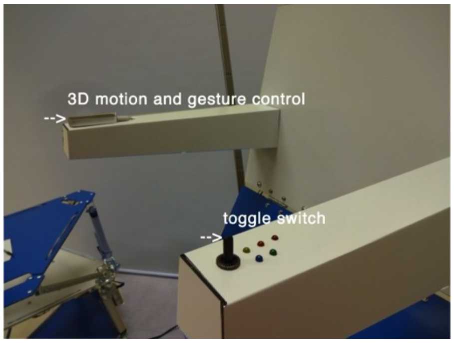

Figure 10. Chair armrets sensors and input control devices.

The leap sensor tracks the x, y, z position of the user's outstretched hand facing palm down. The table manipulation motion mode tracks motion in the plane defined by moving the hand left, right, up and down. Hand motion is directly mapped to table motion: moving to the right moves the table to the right, etc. If the user holds their hand centered over the leap, the table motion ceases. The wall is manipulated by moving the hand left, right, and along a desired direction of extension. Moving the hand to the left or right determines whether a section will move left or right, whereas extension determines which panel will be moved.

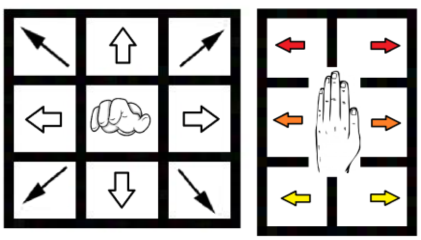

Figure 11. User hand gesture palette. Left: user movement options (uotstretched hand facing down): in table mode, table simply follows hand directions. Right: in screen model, user additionally selects a given panel of the screen to move (red: end, orange: middle, yellow: base).

IV. EXPERIMENTAL EVALUATION

Once the suite was constructed and had completed initial testing, we evaluated the system with volunteer elder subjects (figures 12-16). Users found it easy to use the chair controls to manipulate the table into different heights and proximity (figures 12, 14). The aesthetics of the table movement were pronounced to be pleasant. They also found the chair raising assist (figure 13) sufficiently supportive and easy to control.

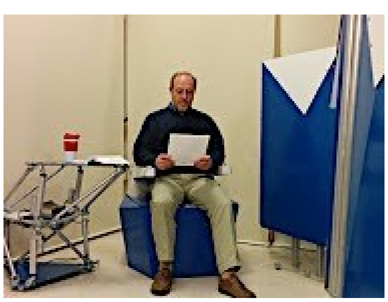

Figure 12. User seated within suite. Table at medium height.

Figure 13. Chair raising user to standing position.

Figure 14. User standing using table (rasied to its full height).

One 89 year old user had initial difficulties positioning her hand at the correct distance above the leap (figure 15).

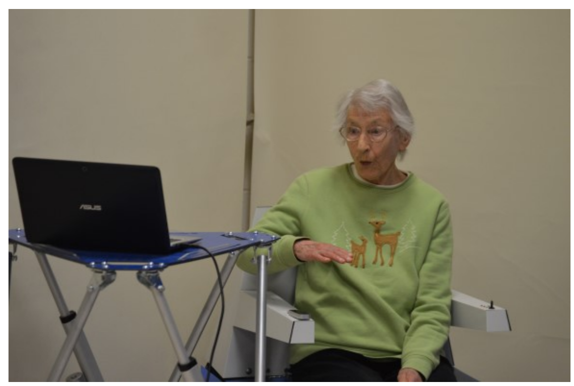

Figure 15. User using gesture interfaces to regulate table height.

However, once she adapted to the correct height, she was able to control both table and screen (figure 16).

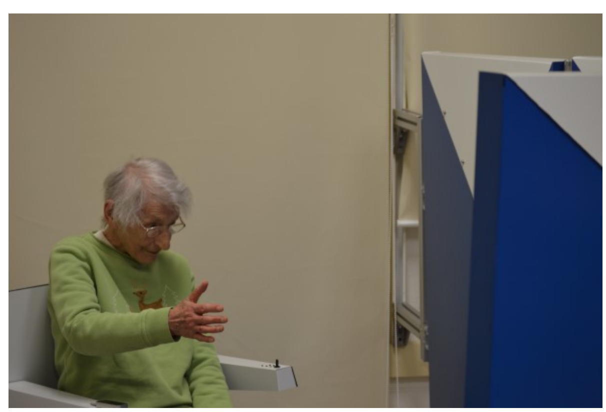

Figure 16. User using vertical hand gesture mode to move screen closer.

Responses were more mixed regarding the screen interface. The extra complexity of the user interface for the screen made (minor) training necessary. Users liked the concept of creating a more intimate space by drawing the screen elements closer. The suggestion was made of implementing a fall detection system within the screen.

In ongoing and future work, we plan to conduct formal usability tests with a larger group of seniors, in order to establish statistically significant findings. In terms of functionality of the system, the leap gesture implementation needs to be expanded to allow for saving configurations of the *home+* suite, as well as for sending and receiving data from remote *home+* items. Self-contained social robots (such as the "echo" or the impending "jibo" systems) can be added to the suite ensemble, to further explore elder/robot social interaction. See figure 17.

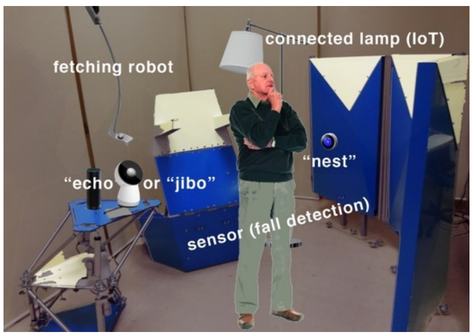

Figure 17. Potential future enhancements to system.

V. Conclusion

We have introduced a novel suite of robotic furniture, aimed at assisting elder users as they age in place. The suite of elements – chair, table, and screen – are controlled by the user from the chair. Design goals, physical realization, and initial experimentation with the suite are discussed.

Acknowledgment

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