Robotic alternatives for bedside environments in healthcare

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***Abstract*—**We present ART, a new concept for a novel reconfigurable bedside environment featuring a suite of networked, robotic components. Physically, the system is the hybrid of a typical nightstand found at home and the over-the-bed table universally found in hospital patient rooms. It is comprised of: smart storage volumes that physically manage and deliver personal effects; a table surface that gently folds, extends, and/or reconfigures to support work and leisure activities; and an accessorized headboard. These robotic components recognize, communicate with, and partly remember each other in interaction with human users. The system is designed to be deployed in a typical healthcare facility or within any domestic interior. The work is aimed at increasing the quality of life of both healthy individuals and persons with impaired mobility and cognitive functioning by intelligently supporting their interaction with their environment. We describe both the overall vision, an implementation scenario, and a working prototype of the system.

***Keywords*—**Architectural robotics, aging-in-place, healthcare, assistive robotics.

I. Introduction

MEDICAL facilities and healthcare personnel are overextended and costly; and with the graying of the population there is a smaller segment of the population to both care for and pay for the well-being of the older and clinical population. While in hospitals, technology has become pervasive and indispensable during medical crises; in our homes, technology supporting health and well-being proliferates as software systems and potentially, but much more slowly, as assistive "humanoid" robots [10], [11].

Meanwhile, the everyday environments in which people live everyday lives – even those homes integrating "Universal Design" – remain essentially conventional, low-tech and ill-adapted to dramatic life changes. Despite an overwhelming preference to live at home [3], and a surprising receptiveness to new technologies in the home [8], [9] and outside it [1], many people with reduced mobility, temporarily or indefinitely, are resigned to live in expensive care facilities staffed with costly and overextended healthcare personnel. This urgent crisis places increasing strain on healthcare and family support systems, and represents a failure of science, engineering and architecture to support a population wishing for independent living. The dramatic demographic shift to an older population, globally, highlights this failure and demands urgent response.

Our approach to aging in place [7], [12], [13] represents a significant departure for robotics in healthcare. Our trans-disciplinary and trans-generational team is realizing **home+**, an intelligent physical environment featuring a suite of networked, robotic components distributed across any domestic interior. **home+** is aimed at increasing the quality of life of both healthy individuals and persons with impaired mobility and cognitive functioning by intelligently supporting their interaction with their home environment. This paper is focused on a key discrete component of the larger **home+** project: an Assistive, Robotic Table **[ART]**. Physically, **ART** is the hybrid of a typical nightstand found at home and the over-the-bed table universally found in hospital patient rooms, comprised of: a smart storage volume that physically manages and delivers personal effects; a table surface that gently folds, extends, and reconfigures to support work and leisure activities; and an accessorized headboard. These aspects of **ART** recognize, communicate with, and partly remember each other in interaction with human users and, as we envision, with other **home+** components.

We envision **ART** supporting and enhancing people in domestic environments over the greater part of their lifetime. To realize this considerable ambition, **ART** is being developed to accommodate three target groups characterizing three conditions of many people over long time periods: (1) those wishing to age in place, (2) hospital and rehabilitation patients who plan to return to their own home, and (3) high-functioning independent individuals. Facilitated by a novel ceiling-suspended sensor parasol that tracks intimate human capabilities [13], **ART** "ages in place" with the people in it.

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Under recently awarded funding, fundamental research involving hardware, sensing and usability is being conducted by Clemson University investigators (the first three authors here) in ECE (Robotics), Architecture (Intelligent Environments) and Psychology (Human Factors) in university labs as well as in our purpose-built **home+** lab, a complete apartment dwelling of our design, realized within the *Greenville Hospital System University Medical Center* [GHS], South Carolina, USA. Our team's key three year deliverable is the full-scale, working prototyping of **ART** to perform "awaking" and "going-to-bed" scenarios for the three target groups defined in the previous paragraph.

This research enables advances in each of the participating communities: (1) for Geriatrics and Rehabilitation, in providing technological means to increase independence; (2) for computer science, a novel "sensor parasol" and associated decision-making software designed to capture and analyze close-range human behaviors in intimate living spaces without the difficulties and privacy concerns of camera-based sensing and sensors attached to the body [13]; (3) for architectural design, the combination of high aesthetics and high-technology in a novel interactive, "architectural robot"; (4) for Psychology, the innovative approach to human mobility and its metrics; and (5) for robotics, a novel morphing "continuum" (table) surface with associated human interface that behaves in a "soft" and life-like way well-suited to interacting with people in intimate physical surroundings.

While there is previous work in adaptable housing for aging in place [9], and specific applications of intelligent machines to aging in place [8], the main thrust of this work represents a departure from other approaches: the creation of intelligent, adaptive physical-digital *environments* for aging in place. **ART** features intelligent behavior and robotic elements in contrast to more typical assistive technologies or medical robotics designed as *substitutes for people*. We envision **ART** and the larger **home+** vision as integral to one's living space. **ART** aims to augment the domestic interior to become a more inviting, responsive and accommodating environment for aging in place, encouraging inhabitants to do tasks for themselves, yet providing assistance when needed.

II. DEFINITION AND ENVISIONED OPERATION OF ART

Initial design efforts envisioned **ART** having four key components (Fig. 1):

• ***A smart night stand*** manages, stores and delivers personal effects, including medical supplies, and communicates to caretakers when eyeglasses and other belongings are not moved over a period of time. It accommodates audio and touch screen computing technologies.

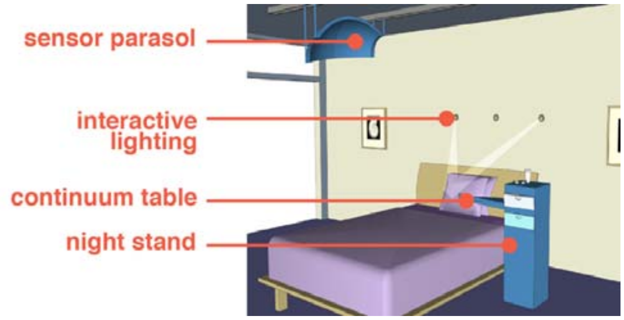

Fig. 1 an early concept sketch of **ART**, with its key aspects identified.

• ***A continuum table*** gently folds, extends, and/or reconfigures to support work and leisure activities.

• ***An accessorized headboard,*** intended for installation behind the bed, sofa, or chair, provides adaptable support and allows for user and intelligent control of task lighting (on/off, dimming and direction).

• ***A sensor parasol***, ceiling suspended, tracks intimate human needs and capabilities. Physically, we envision this novel "sensor parasol" as a carefully arrayed suite of motion sensors mounted to a morphing surface allowing for detection of human behaviors in an intimate living space (e.g. near and around bed, sink, reading chair) without resorting to potentials invasive cameras and body-worn sensors.

These four aspects of **ART** recognize and communicate with each other in interaction with humans and, we envision, with other **home+** components. *Note that figure 1 and figure 3 (to come) are merely sketches of how ART might look and behave.* Our team facilitated early explorations of **ART** in engagement with a graduate course for Architecture and ECE students taught by the authors (Fig. 2 shows some of these). These figures represent not a fixed, pre-determined design, only an early state of our research team's continuing iterative design and evaluation over the ongoing development of ***ART***. This paper describes advances in the first 3 **ART** components.

III. SCENARIO FOR A FULL SCALE DEPLOYED SYSTEM

Integrating the hardware, software and sensing aspects of **ART**, two scenarios follow of how **ART** might look and operate, focusing on "Andrea" "Getting out of bed" and "Going to sleep". These two scenarios best afforded the research team the opportunity to demonstrate a wide-range of human/system behaviors and consequently define the research scope of the key deliverable for this research: the iterative

Fig. 2 alternative "sketches" of what an **ART** nightstand might look like (our iterative design process has just begun).

design, performance and evaluation of a full-scale **ART** prototype operating autonomously in our purpose-built **home+** lab supporting numerous participants representing three target groups.

"Andrea" is a 58-year-old Professor of English living independently and actively. In the first scenario, "Getting out of Bed," Andrea is in a hospital room following her treatment from a fall from which she sustained a shoulder injury (Table 1 and Fig. 3 – left). **ART** considers such context as time of day, Andrea's personal data, and in a novel way, her behavior at close range via the sensor parasol. Using this information, the system detects Andrea's activities and gestures to plan and execute appropriate responses.

The second scenario, "Going to Sleep," and **ART**'s participatory role, is described in (Table 2 and Fig. 3 – right). Here Andrea has been released from hospital and is convalescing at home, where a "home" version of **ART** has been installed. Andrea's capabilities are still restricted, the sensor system detects this and tunes ART's responses accordingly, in order to both help Andrea at the moment and also aid her recovery.

In the Tables (1 and 2) the scenario is broken down into the interrelated activities of the three key players: Andrea (column 1), **ART**'s hardware system (column 2), and the software system coupling the two together (column 3). The events, in chronological order down the table, for the two scenarios, are detailed in column 4.

IV. SYSTEM PROTOTYPE

Our research team – trans-generational and trans-disciplinary - has extensive prior experience in creating robotic environments [2], [4], [5]. Exploiting this expertise, pilot work on the **ART** project included research on its human factors aspect, its sensing aspect [13], and its overall, rough-but-working "proof of concept" demonstration of **ART** (created in hardware and software as a "sketch" prototype over several weeks) (see video link [6]).

Following and expanding on the above initial work, a full-scale hardware prototype of **ART** was constructed. The prototype consisted of four interrelated elements: a continuous "continuum" table, whose shape and stiffness are alterable by the user; interactive "storage boxes" embedded within the table; a mobile nightstand retrieval element; and a robot headboard to promote comfortable reclining. Each of these elements is described in the following paragraphs.

For the **ART** continuum table prototype design, the decision was taken to concentrate on the "morphing" table

Fig. 3 **o**ur early renderings of **ART** and "Andrea" interacting. [left] – getting out of bed during a hospital stay; and [right] – going to sleep at home.

Table 1. scenario 1. getting out of bed.

User	Hardware System	Software System	Scenario Step
		1	ART initiates its morning reminder service for family visits, nephew’s birthday, etc.
	2		ART displays the day’s appointments: Dr. visit, nephew’s birthday, etc.
3			Andrea decides to read for a while before beginning her day. She gestures for the novel she has been reading (overriding system expectations).
	4		ART’s nightstand component senses the gesture.
		5	ART locates the stored novel in its inventory.
	6		ART’s nightstand retrieves the novel and extends the overbed table to offer it to Andrea.
7			Andrea reaches for the book. She reads for twenty minutes to complete the previous night’s chapter and then replaces the book.
	8		ART’s nightstand component stores the book.
		9	ART logs the location of the stored novel.
		01	ART plays a prerecorded message from Andrea’s young grandchildren which she enjoys.
		11	Previous data show a decline in mobility.
	12		The bed lowers to facilitate Andrea’s transition to a standing position
13			Andrea gets out of bed

Table 2. scenario 2: going to sleep.

User	Hardware System	Software System	Scenario Step
1			Andrea sits on the edge of the bed
	2		The pressure mat beneath the bed detects her presence.
		3	Previous data show a decline in mobility
	4		The bed rises to a reclining configuration to reduce back strain.
5			Andrea reclines on the bed
6			Andrea reaches (gestures) to ART's bedside table for the novel she has been reading
	7		ART senses the gesture
		8	ART uses current context to initiate transfer of Andrea's novel
	9		The nightstand retrieves the stored novel, approaches, and extends the overbed table to offer it to Andrea
10			Andrea has difficulty lifting the heavy hardcover novel.
	11		ART's nightstand senses the slowness of the transfer
		12	ART executes exception handling; repositioning book by extension of table
	13		The nightstand repositions the book closer to Andrea to ease the handoff
14			Andrea obtains her book
15			Andrea reaches (gestures) to actuate the overhead reading light
	16		The environment senses the gesture
		17	ART determines reading session beginning, brightens overhead reading light
	18		The environment slowly brightens the reading light
19			After reading, Andrea replaces the book and dims the lights
	20		The side-table stores the book
		21	ART adds the book to its inventory database.
		22	ART logs Andrea's reading time as a possible wellness metric.
		23	ART uses current context to initiate storage of Andrea's reading glasses.
	24		The side table offers the receptacle in which Andrea's eye glasses are stored
25			Andrea places her bifocals in receptacle, gently pushes (gestures) nightstand away
	26		The sidetable stores away the bifocals and withdraws to its resting position
		27	ART adds Andrea's glasses to its inventory database.
		28	ART uses current context to initiate posing the room into sleep configuration.
	29		The bed lowers to a lying configuration
	30		Low level lighting slowly dims and turns off
	31		ART plays soft music until Andrea falls asleep
32			Andrea goes to sleep.

surface. An innovative passive (i.e. user-shaped, as opposed to actuator-driven) design was selected. Based around a rigid backbone, a curved design was adopted (see Fig. 4). The table can pivot about its base (at right in Fig. 4). However this was not actively actuated in the prototype.

Fig. 4 continuum **ART** table.

The table was "hand-morphable" at its leading and trailing edges (as viewed by the bed occupant). These edges were formed by encasing a large number of small polystyrene balls within a shaped plastic casing (fixed to the rigid part of the table) capable of sustaining negative pressure. See Fig. 5. At standard (i.e. room) pressure, the edges are soft and compliant. However, when negative pressure (applied via a conventional vacuum cleaner to a standard interface) is present internally, the table edge elements "stiffen". At medium pressures, the internal balls allow the edges to be hand-shaped by the user, to produce a stiff surface locally shaped by user preference. This simple and elegant design allows tunable compliance to be introduced at arbitrary locations, and with pre-selectable shapes, in the table.

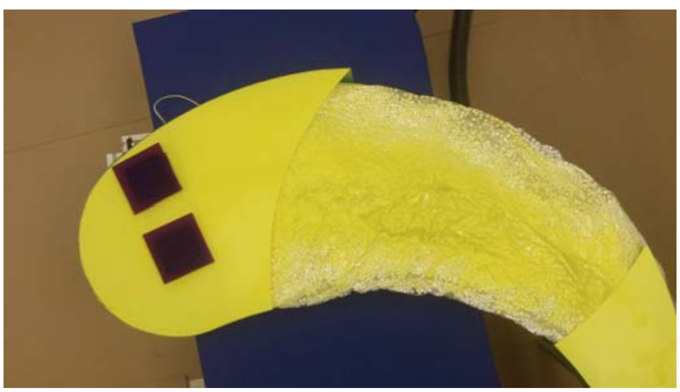

Fig. 5 **ART** table – morphable edge.

In tests, the table was successfully molded by the bed occupant into a variety of shapes. In addition to the basic flat shape, three forms were found particularly useful: (1) a "close reading" configuration, where by folding down (and then back up at the lip) the proximal edge of the table, a book could be supported at an angle selectable by the bed occupant; (2) a "far reading" configuration, where by folding up the distal edge of the table, a book could be supported at distance, again at an angle selectable by the bed occupant; and (3) a "cup/bowl" shape, where the bed occupant could form a "crater" in the table to firmly support bowls (of variable sizes) for consuming food, or for use as a cup holder. See Fig. 6.

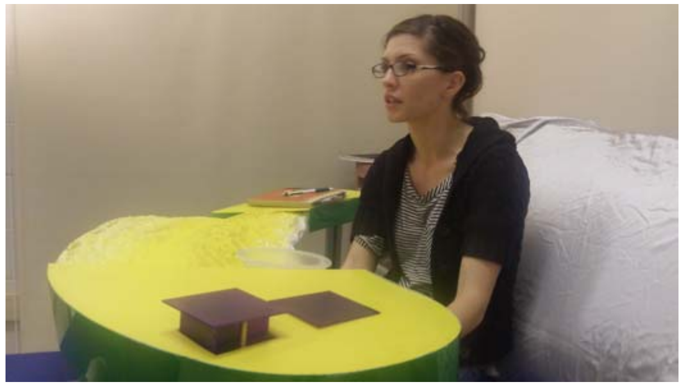

Fig. 6 moldable table surface – note bowl embedded in patient-created recess.

Further automation of the above table design is very feasible. We are currently conducting research on active shaping of continuum table surfaces (using tendon-based designs using electric motors, and pneumatically driven designs using McKibben (air) muscles. The next ART table prototype is expected to include the more promising of the two above actuation strategies. Future iterations of the design would also include active actuation of the table end pivot point (to allow the table to be rotated away from the bed, to facilitate the user getting out of bed and access for care personnel).

The next two elements in the **ART** prototype concentrate on storage and delivery of personal items to bed occupants. A key difficulty faced by caregivers is that patients often cannot move sufficiently to retrieve items they need. Though trivial in nature, this task is repetitive and places a burden on caregivers, relatives, etc.. Additionally, waiting for others to retrieve everyday things increases the frustration of patients as they become increasingly aware of their relative immobilization.

The first solution, embedded within the continuum table and intended for storage and retrieval of small personal items, was of small boxes embedded in the table, above its pivot point (see Fig. 7). These boxes smoothly emerge vertically from the (formerly smooth) table surface when activated by the user, and retract again on command.

Fig. 7 spring-loaded storage boxes.

The box concept was successfully implemented in the continuum table. Two boxes, made of acrylic, were flush mounted on the table surface (Fig. 7). The spring-loaded boxes were retracted by servomotors winding a tendon against the springs. See Fig. 8. Actuation (open and close) was implemented as a non-contact operation, using a proximity-activated infra-red sensor mounted. (The user moved their hand above the sensor for a minimum amount of time.) However contact-based solutions using, for example, capacitive contact sensors, are quite feasible.

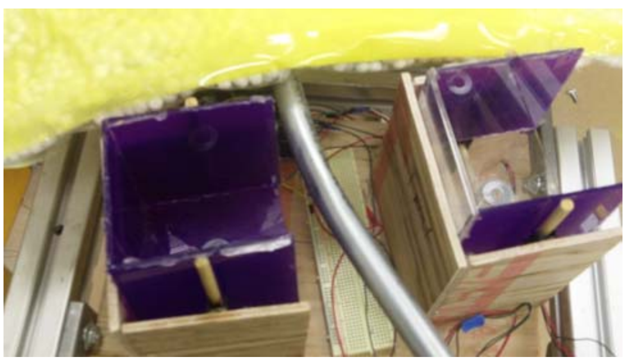

Fig. 8 box design detail.

This simple design proved quite effective. Implemented in a commercial version of **ART**, such boxes could hold personal effects such as glasses. Additionally, activation of some boxes could be timer-based, for timely delivery to patients. Thus, nurses could store medications in the units, set the timer, and provide patient access to the medication when appropriate.

A second novel storage solution concentrated on a robotic alternative to the traditional nightstand system. Patient access to, use of, and satisfaction with, traditional nightstands is quite limited. The main issue is the relative inaccessibility of much or all of the nightstand storage space. Therefore, we augmented the **ART** prototype with a "personal assistant" mobile robot, designed to retrieve and store personal items from a traditional drawer system which a patient is incapable of accessing.

The key design decision taken for the prototype was to retain the traditional remote nightstand, but augment it with the mobile personal assistant robot. The personal assistant (see Fig. 9) was designed to have a small "footprint" to enable it to operate in tight spaces in hospital rooms or bedrooms. Featuring a vision system, it was able to recognize an item based on either the item itself or a picture of the item on a card. The patient could either show the item or flash the card to the assistant, which then recognized which item to retrieve/store and acted accordingly.

Fig. 9 **ART** "personal assistant".

The prototype mobility was provided by a commercial Pioneer mobile robot base. On the base was mounted, via an aluminum frame, a "fork-lift" end effector which transported drawers between the patient and the nightstand. The fork lift mechanism was moved to match the needed heights by a prismatic joint driven by electric motors (Fig. 10).

This personal assistant robot functioned effectively as a drawer transfer system. The system remembered which items were place in which drawers, relieving the patient of this burden. As implemented, the vision recognition system is based off color-coded cards. However, other approaches such as a template-matching system are quite feasible. Additionally, numerous other mobile robot designs are quite feasible for this application.

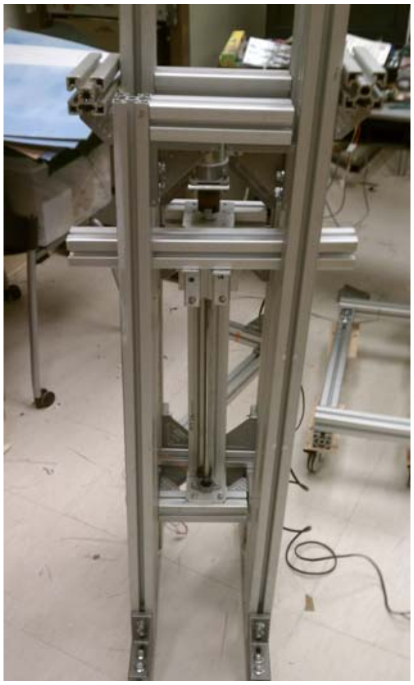

Fig. 10 **ART** "personal assistant" structure.

Finally, in order to further increase user comfort, an animated headboard was created (Fig. 11). Conventional bed/headboard combinations (particularly in hospital environments) result in complaints of discomfort when sitting or reclining on the bed watching TV, reading books, or using portable devices. A common solution is to pile several pillows against the headboard to provide back support. However, this temporary solution often suffers from lack of support and requires regular re-organizing of pillows – not easy for many hospital room occupants.

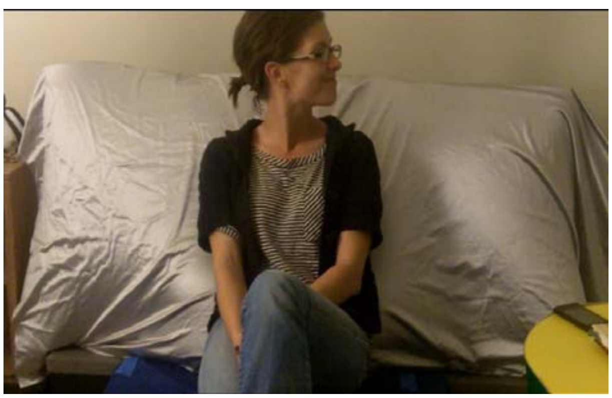

Fig. 11 **ART** reconfigurable headboard.

To address the above issues, we created a programmable compliant headboard whose shape can be adapted to user needs and preferences (Fig. 11). For this novel **ART** prototype headboard, six inflatable bladders were embedded within the headboard and were adjusted as needed to vary the location and stiffness of support for the upper torso of the bed occupant. (This system can potentially also offer back massage.)

The bladders were actuated by six pneumatic actuators. Each bladder element was independently actuated by a pressure regular to maintain a specified size. Each element consisted of an air chamber, a pressure regulator and an infrared chamber size sensor. (The infrared sensor was embedded inside the bladder element, sensing its size within a given pre-tuned range.) A central controller was connected to each element and implemented closed-loop control for each individual element. The central controller also accepted remote user commands. See Fig. 12.

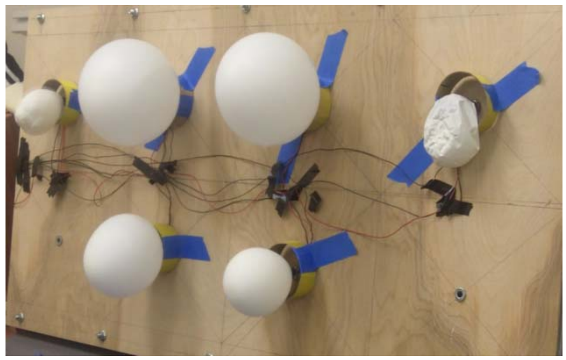

Fig. 12 **ART** headboard internal bladders.

The headboard successfully conformed to a wide range of user sitting and reclining positions. However, the material/pressure combinations were insufficient to prevent rupture of some of the bladder elements. It is anticipated that more refined materials selection and specialized bladder manufacture can solve these problems in future designs.

The overall prototype system was informally evaluated by users (graduate students) in our laboratory, and feedback was very positive. Our current efforts focus on more formal user evaluation, and design and manufacture of a next generation more refined design, suitable for installation and evaluation in our **home+** laboratory in the Greenville Hospital System University Medical Center.

V. Conclusion

This paper has introduced and described **ART**, a novel reconfigurable bedside environment featuring a suite of networked, robotic components. **ART** is a robotic solution to intelligently combine and reconfigure the typical nightstand found at home and the over-the-bed table universally found in hospital patient rooms. The **ART** concept comprises: smart storage volumes that physically manage and deliver personal effects; a table surface that gently folds, extends, and/or reconfigures to support work and leisure activities; and an accessorized headboard. The system is designed to be deployed in a typical healthcare facility or within any domestic interior.

We have described both the overall vision for, and a working prototype of, the **ART** system. The design goals are evolved by scenarios of anticipated use of the system. The hardware prototype features a new and novel compliant continuum table, as well as an adaptable robot headboard and smart storage elements. **ART** has the potential to be life changing, allowing the aging population to age in place; allowing clinical populations more independence; and allowing healthcare professionals to increase the quality of their interactions with their patients.

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