

From Components to Caring: The Development Trajectory of a Socially Therapeutic Assistive Robot (STAR) Named Therabot™



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Abstract—Designing a socially therapeutic assistive robot (STAR) for use in mental healthcare is an emerging interdisciplinary process, for which there is a lack of comprehensive guidance and standards. This paper provides insight into the design and development process of the socially therapeutic assistive robotic dog, Therabot™. By outlining the project’s eleven-year history, exploring a snapshot of its current state, and discussing its trajectories we aim to share a useful glimpse into the processes that guide the creation of a STAR.

1. Introduction

The use of social robots in the mental healthcare domain for therapeutic purposes holds great promise and carries considerable potential for a positive societal impact. However, the process of shepherding a robotic platform from design sketches, through hardware/software prototype development, cycles of iterative refinement, and ultimately into the role of a useful therapeutic entity is not trivial. While social robots have undoubtedly had measurable positive impacts upon the world, the scope of opportunities remain far-reaching.

This paper reflects on the design path of the socially therapeutic assistive robot (STAR) named Therabot™. Through this examination we seek to present and preserve a cross section of the research and development processes that are less frequently examined in literature. Although Therabot™ has made substantial progress as a robotic platform over the past eleven years, a path of tremendous refinement remains.

We begin by providing background on social robots in mental healthcare and approaches to their development in Section 2. In Section 3, we describe the most notable portions of Therabot’s creation with increasing detail on more recent developments. Subsequently, Therabot’s design goals and development methodology are presented in Section 4, followed by an overview of ongoing development activities described in Section 5. Finally, in Section 6 we conclude with a look toward the future and discuss the areas we believe will be most relevant over the coming years.

2. Related Work

Therabot™’s intended purpose is to provide a therapeutic benefit in clinical mental healthcare. This section reviews the domain of social robots within mental healthcare and provides background on the approach to system creation and refinement known as participatory design.

2.1. Socially Assistive Robots in Mental Healthcare

Socially assistive robotics (SAR), a specialized area of social robotics, which focuses on robots that help users via social interaction [1], is a rapidly developing and vibrant area of study within human-robot interaction (HRI) research. A subset of research efforts in SAR focuses specifically on the use of socially therapeutic assistive robots (STARs) in clinical mental health interventions. These efforts are

distinct from other social robotics endeavors in that they are typically developed in collaboration with clinical experts and are intended to ultimately produce a therapeutic effect validated at the same level as other treatment components.

In a 2015 review, Rabbitt et al. examined the use of SARs within mental healthcare and presented priority directions for research related to the use of a SAR within mental healthcare [2]. This review highlighted the limited scope of a SAR within mental healthcare, the lack of a strong evidence base for their effectiveness, and a need for expanded and closer collaboration between mental health professionals and HRI researchers. Specifically, SAR applications with the most rigorous evidence bases were those focused on autism spectrum disorder and older adults experiencing cognitive decline. A systematic review of randomized controlled trials (RCT) of robots for mental health interventions conducted in 2019 by Robinson et al. reveals a relatively similar landscape with work in this area remaining sparse and still in early stages [3]. This sparsity is found across three dimensions: (1) the social robots utilized, (2) the problem areas treated, and (3) the patient groups examined. The most investigated areas remain children with autism spectrum disorder and older adults. Other recent systematic reviews have also described the limited nature of evaluations of SARs and highlighted the opportunities for expansion in scope, populations, and evaluation measures [4], [5], [6].

While prior research has been limited in scope, it is important to note that broader contributions are emerging as more research focuses on SARs. For example, Robinson et al. have recently conducted RCTs focused on behavioral interventions related to calorie intake [7] and mindful breathing techniques [8]. Focusing on the domain of medical diagnostic procedures, Trost et al. conducted trials that demonstrated SARs were useful in decreasing pain and fear during pediatric IV placement [9].

Apart from the resource intensive efforts required, a formidable challenge in the development and evaluation of SARs for mental healthcare is the vast array of fundamental questions related to ethics and privacy that must be addressed for each use case. For a comprehensive examination of these issues we recommend review articles by Lutz et al. [10], Koutsouleris et al. [11], Fiske et al. [12], and Khanna et al. [13]. As emphasized by Rabbitt et al., establishing evidence-based treatments involving SARs within mental healthcare is a lengthy process, which requires substantial investment across disciplines and poses a wide range of design questions and integration challenges [2]. As described throughout this paper, our experiences striving to develop Therabot™ into a useful clinical tool within mental healthcare reflect the many challenges documented by researchers working toward similar goals.

2.2. Participatory Design

Participatory Design (PD) is a design approach that emphasizes empowering all stakeholders to actively collaborate with designers and developers in shaping the way a system is constructed and deployed [14]. This approach involves

the stakeholders of a system in the generation of ideas and design rather than exclusively in a requirements issuing or evaluative role. The PD process may occur across phases of a system's development, involving stakeholders in an iterative process until a suitable solution emerges.

Most relevant to Therabot™'s design process is the PD methodology described by Lee et al. [15] for the purpose of designing social robots to support mental healthcare. This methodology encourages participants (e.g., clinicians, clients, staff, etc.) and researchers to engage in a process of mutual learning, aiding in achieving a common ground in which each can present their concerns and work toward solutions. In this paradigm users are considered contextual experts and researchers strive to gain a comprehensive understanding of the contexts experienced by each user of the system. This is achieved through a series of interactions (i.e., workshops) in which researchers and participants work together to share knowledge and iteratively design a system. Initial sessions work to familiarize participants with existing robots and gain feedback about these systems and how they might fit into the participant's daily activities. Participants and researchers then work together iteratively designing new robotic systems that could support the participant's activities. Throughout these cycles, researchers provide participants with insights into the technical aspects of social robots and present opportunities for interactive understanding of components like actuators and sensors. Ultimately the process yields a robotic system shaped for the nuances of the specific context it will inhabit.

3. Design Trajectory

Since Therabot™'s inception in 2012 the platform has accumulated a rich set of design and development approaches, successes, failures, and iterations. In this section we provide a brief summary of the first seven years of platform development (for a thorough description of these years see [16]), followed by a more detailed accounting of significant developments over the past four years.

3.1. Foundational Work (2012-2018)

Therabot™, designed to resemble a stuffed-animal dog, is the culmination of extensive research and collaboration [16]. The robot's outer appearance was informed by feedback from an online survey of 1045 participants¹. Utilizing results from this design survey, we then began evaluating which qualities were most important for a support companion by conducting an open-ended survey of 36 past trauma survivors regarding their experiences using comfort objects and potential desired features for a robotic support companion. Before transitioning to the prototyping phase, we also conducted an open-ended survey with 13 clinicians to explore their anecdotal experiences with patients and how they envisioned utilizing a support companion in their therapeutic practices.

1. Details available at: <https://stars.msstate.edu/designsurvey>

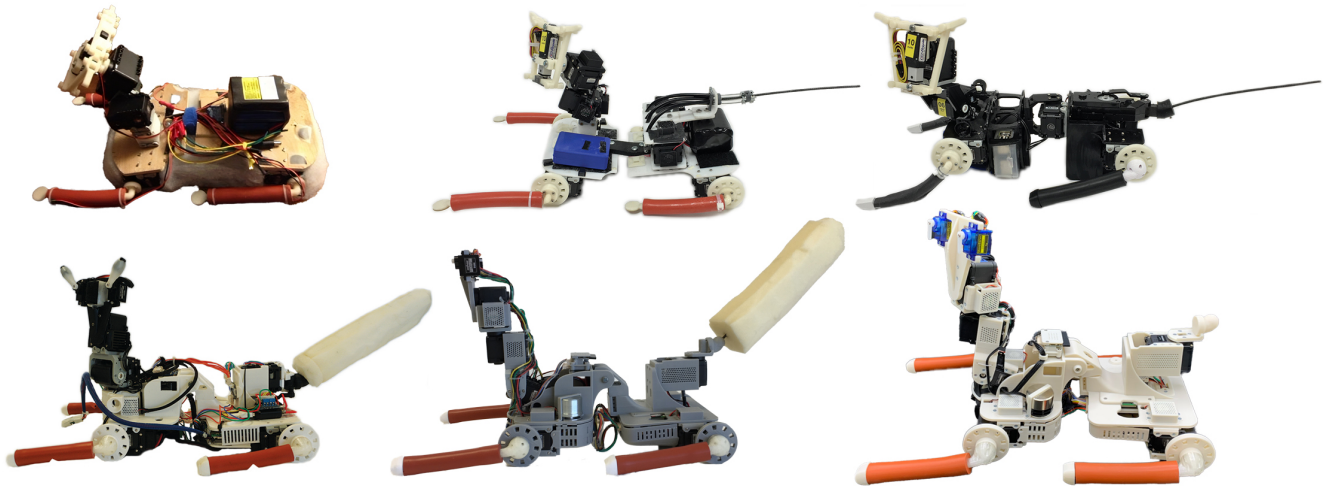


Figure 1: TherabotTM's internal structure at major milestones throughout the project's history.

Following an analysis of the data collected in these studies, a set of requirements was synthesized and an external consultant was commissioned to fabricate the robot's hardware while the research group developed software [17]. Ultimately, after extended delays the external consultant was unable to deliver a hardware platform capable of meeting the design requirements or functioning in a reliable manner to be useful in research.

In late 2014, the research team began development of both the hardware and software systems. The form-factor of a beagle-shaped stuffed animal was used as a starting point for the overall form. This concept was then refined to accommodate the integration of electronic and mechanical components, necessitating space within the outer layer along with ample padding to create a soft feel. For the outer layer, two different "mini minky shaggy" fabrics were selected. These fabrics were characterized by their soft, fur-like texture with the body fur longer and a shorter pile length for the muzzle and the bottom of the paws. The robot's mechanical structure was surrounded by a padding layer encased in 4-way stretch material. The padding was then covered by separate exterior coverings for each leg, the head, and body. The exterior covering of the head and body connect at the base of the robot's neck and along the underside of the robot using hook-and-loop fasteners. Additional padding was sometimes added under the covering and on top of the encased padding to fill in low spots in the covering to shape the robot. The initial prototype, demonstrated at the 2015 HRI conference [18], was fabricated by hand with the primary internal structure composed of two flat wooden platforms held together by a thick rubber strip. Components attached to the internal structure included actuators for each leg, a three degree-of-freedom neck, two degree-of-freedom tail, piezoelectric and capacitive touch sensors, an inertial measurement unit, and a microphone. The design progression of the internal structure of the robot over time

is shown in Figure 1.

The initial prototype was improved by using CNC machining and 3D printing to build the internal structure. The internal padding was updated to facilitate easier assembly and operation. Following these updates, in early 2016 we conducted a collaborative design study where sixteen participants interacted with two versions of TherabotTM (one with the robotic structure, stuffed and covered, but powered down and the other a stuffed animal only, with no robotic structure) and completed a semi-structured interview (see [16] for further detail).

Following this design study, the robot's hardware and software were further refined with an emphasis on creating interactive behaviors that allowed the robot to be responsive to its surroundings. The robot's touch sensing system was optimized using capacitive fabric located throughout the body paired with basic machine learning approaches to classify touch interactions. The robot's internal mechanical structures transitioned to be mostly 3D-printed and the collar was modified to include RGB LEDs to indicate the robot's status and power connectors for charging were located in a leash attached to the collar. The software architecture was refined to provide higher level abstractions for designing the robot's movements and stimulus-based behaviors.

TherabotTM's internal structure was composed of 3D-printed ASA plastic sections, a pivoting joint, and rubber legs actuated by Dynamixel AX-12A smart servos. Rubber legs were used to allow flexibility during interactions. The neck and head assembly used three Dynamixel servos for pan, tilt, and roll, and two SG90 servos attached to the head actuated the robot's ears. The plastic sections providing the structure for the robot's body housed components including a Raspberry Pi 3A+, a USB Dynamixel motor interface, a Teensy 3.2 microcontroller, a lithium-ion battery, and an audio surface transducer. Sensors, an inertial measurement unit and boards to support capacitive touch sensing, were



Figure 2: Therabot™’s current exterior appearance.

also supported by this frame. The software was primarily written in JavaScript and executed in a Node.js runtime, excluding the microcontroller code. A web interface allowed configuration of the robot and provided status information to represent its sensing and actuation. This version was demonstrated at the 2018 HRI conference [19].

3.2. Recent Work (2019 - 2023)

In early 2019 we conducted a study in which 32 participants engaged in a structured interview about anxiety (derived from the American Psychiatric Association’s Structured Clinical Interview, SCID-5-CV) while holding either an interactive Therabot™ robot, a stuffed animal version of Therabot, or nothing. Following the interview, all participants interacted with and provided design feedback related to the interactive version of Therabot (results are reported in [20]). Section 5 in this paper discusses how we are currently implementing features based on participant feedback.

In order to move Therabot™ toward clinical use, the project expanded to include multiple HRI research groups collaborating with each other and with the intended users of the robot (e.g., clinicians, clients, etc.). Beginning in late 2019 researchers at the R-House Laboratory for Human-Robot Interaction (led by Dr. Selma Šabanović) at Indiana University and at Hanyang University (led by Dr. Casey Bennett) joined with the existing team at the Social, Therapeutic, and Robotics Systems (STaRS) Lab at Mississippi State University to work toward integrating the robot into therapeutic interventions for individuals with chronic depression. The R-House research group has valuable experience and expertise in developing and utilizing participatory design methods for STaRS within mental healthcare contexts, an essential element for guiding the robot toward producing a useful therapeutic effect. Dr. Bennett has ex-

pertise in developing AI and ML techniques within clinical contexts, and his group’s focus is on developing models of sensor data that modulate the robot’s behavior, a critical element of an adaptive therapeutic system.

Through this collaboration we are working to understand how Therabot™ can contribute to effective interventions for individuals diagnosed with chronic depression. As described further in Section 4.2, our research approach uses an ongoing participatory design process to provide a strong signal for guiding the design and iterative refinement of the hardware and software that ultimately facilitate the interactions between humans and the robot.

In the following sub-sections we first summarize the participatory design work that has been conducted from 2019 through early 2023. Next, we discuss the development and use of a supplementary hardware device that allowed for the evaluation of sensors and the collection of contextual data across a variety of social robots deployed in home settings. Finally, we describe the technical changes to the robot that have occurred during this timeframe as a result of knowledge gained from the participatory design and supplemental hardware home deployments.

3.2.1. Participatory Design Activities. Over the past three years, our collaborators at the R-House Laboratory for Human-Robot Interaction have employed and further developed participatory design (PD) techniques to work directly with users to gain critical design insights for Therabot™’s development. The PD processes drive the technical development of Therabot while cultivating social and clinical practices that are essential to the usability and effectiveness of the robot in a clinical setting. PD work began with the development of seven workshops for individuals with moderate to severe depression (client workshops) and five workshops for therapists and case workers (clinician workshops).

The client workshops begin by introducing participants to key concepts like STaRS and sensing technologies. Participants then design a customized robot while keeping contextual factors in mind. This design is refined throughout several sessions. Using techniques like “design fiction,” participants explore how their design would function in their daily lives. Finally, participants spend time reviewing their custom designs and conveying their feedback.

Like the client workshops, clinician workshops begin with an introduction to key concepts and progress into designing a robot based on their experiences with their clients. Through design fiction prompts, clinicians provide insights into how they envision robots being implemented in specific scenarios. Finally, clinicians review their robot designs and those of their clients.

In both workshop series, participants spend time examining a variety of existing robots including Therabot™ in its current form. The design process gains insights for the design of Therabot through direct feedback related to its present design and through the general concerns and design ideas that participants present surrounding their context.

The client and clinician series of workshops have been completed by 10 and five participants respectively, and the

cumulative findings are undergoing analysis. Additionally, in a condensed version of the client workshop series ten individuals living with depression designed unique exterior appearances for Therabot, discussed robot behaviors, and provided insights concerning privacy and data collection. While a variety of physical robot designs were produced, participants converged on a preference for a soft exterior, the desire for realistic sounds and movements, and a willingness to share data with their therapists [21].

3.2.2. Modular Sensor Collar. As our team began conducting initial participatory design activities in early 2020, the emergence of the global pandemic necessitated rethinking the best way to conduct our research. As mental healthcare professionals were overwhelmed and the ability to interact in-person was constrained, we shifted our focus to developing a sensor suite that provides the robot with important environmental context.

Expanding upon prior work [22], [23], [24], initiated within the R-House research group, the team developed a modular sensor suite fashioned as a pet collar for attachment to zoomorphic robotic pets used in home environments². Employed as an adjunctive device for robotic companions, the sensor collar aids in understanding human-robot interactions in naturalistic contexts while taking into account the competing needs of flexibility, cost, privacy, and durability.



Figure 3: Fully assembled V1 (top) and V2 (bottom) sensor collar systems with CAD illustrations of their respective compute modules shown on the right.

The sensor collar enables researchers to experiment with different sensors based on PD feedback without the substantial technical investment of integrating them into a robot platform. This is a cost-effective method to test various sensor technologies before finalizing a robot design. Our design (shown in Figure 3) employs a modular paradigm where the sensor collar comprises a central compute module and one or more sensor modules. The compute module handles tasks like computation, power, data storage, and the main user interface; each sensor module offers unique sensing capabilities and is managed by the collar’s compute module. The system resembles a pet collar with attached electronic modules. These modules connect electrically along the collar’s underside. The collar was crafted using a nylon webbing strap, colored ribbon, polyester thread, elastic cord,

side release buckles, and 3D printed tri-glide slides. Wires between each module are channeled through elastic cord stitches on the collar’s inside. We designed and deployed the compute module, a primary multi-sensor module, and the underlying collar infrastructure.



Figure 4: The modular sensor collar worn by Roarin’ Tyler™ & Therabot™

We deployed our sensor suite (as a collar on a dog or cat robot, see Figure 4 for an example of the collar being worn on two different zoopomorphic robots) in different home settings in South Korea and the United States and established ground truth data by using an ecological momentary assessment (EMA) smartphone application, which requested information about participant’s interactions with or around the STAR three times per day, throughout a 2-3 week period. Correlating the ground truth data with data collected within the relevant time frame by the sensor suite and training deep learning models with these correlations created a model with 75% - 80% accuracy at identifying many common household activities [25], [26].

3.2.3. Technical Improvements. Across this time period our technical efforts focused on moving the robotic platform toward a modular yet robust physical design with an emphasis on reliability and consistent fabrication processes. The robot’s design is continuously evolving, and the hardware and software components need to perform in a stable manner without imposing rigid restrictions that prevent design explorations.

Mechanical Design: We transitioned the robot’s mechanical design from a set of disparate processes into a single CAD software system with version control and a primary fabrication method of 3D printing with ASA material on widely available consumer printers. This allows for consistent tolerances and defined physical feature limits. Hardware fastener sizes were standardized, with an effort to use M2 screws paired with heat-set threaded inserts throughout the system. Documentation for the robot’s full mechanical design was established at a level that facilitated fabrication by anyone with ordinary skill in the art.

Actuator Modifications: The robot’s zoomorphic form factor requires an active approach to managing the heat generated by actuators and electronics. The robot’s primary joints are actuated by the widely used and relatively low cost AX-12A Dynamixel smart servos. In their off-the-shelf form

2. Details available at: <https://stars.msstate.edu/sensorcollar>

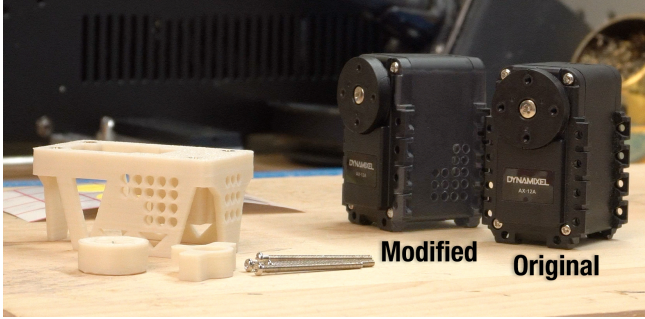


Figure 5: The 3D-printed parts used to modify off-the-shelf AX-12A actuators (left) along with a modified and unmodified actuator (right).

the actuators, composed of a geared DC motor and driving electronics encased in ABS plastic, are unable to dissipate heat quickly enough to remain continuously operational when inside of the robot. We developed a method for adding air ventilation channels to the actuator’s standard casing, which allows heat to be efficiently removed using small fans. The modification process uses custom designed 3D printed parts (see Figure 5) that fit around the actuator to facilitate using a drill in a patterned fashion to create air vents³.

Modular Electronics: In order to accommodate electronic components with differing physical dimensions (e.g., as a result of supply chain constraints) and to create a more robust platform, the robot’s primary structures were updated to allow the attachment of modules containing electronic components rather than incorporating their attachment directly. Additionally, the custom electronics boards that facilitate the routing of power and signals between components were encased in printed plastic parts to improve their durability. In order to support our collaborators assembling and/or fabricating additional systems, the system’s full design was cataloged and a guided assembly manual and videos were produced.

Transducer-Based Heartbeat: Prior to our 2019 design study, the robot’s hardware was updated to include a surface transducer audio output attached to the front internal structure. While initially intended to provide fuller sounds that felt rooted in the structure of the robot, it also proved to be an effective means of simulating a heartbeat to increase the sense of aliveness perceived by users.

Hangtag Interface and Collar: To provide an interface for quick, device-free robot control, updates were made to Therabot™’s collar to include a dog-bone hangtag interface with a screen and three buttons. The hangtag interface offers an easy way to toggle settings such as movement and sound.

The collar serves as an intuitive interface for configuration of and communication with the robot, reducing the need for users to involve a secondary device. It has an OLED screen (SSD1306, 0.96”, 128x64 pixels), three buttons, and eight Neopixel LEDs (SK6812RGBW). The hangtag interface provides toggles for basic functionalities

such as movement, sound, and aliveness. It also displays essential information about Therabot™, including IP address and battery level. Currently, the collar Neopixel LEDs emit a light blue glow. However, future designs might utilize these LEDs to convey more detailed robot statuses. For instance, a pulsing orange light could indicate a low battery, signaling the user to charge the robot soon.

Over the years, the collar’s reliability and aesthetics have evolved significantly. The initial design was adapted from a commercially available dog collar with a paw print design. This approach had its challenges. For instance, the paw print design dictated the placement of the Neopixels, requiring each LED to be individually cut from their original spools, soldered, then affixed into place on the nylon base of the collar to correspond with the paw print design. This method resulted in bumps beneath the ribbon where each LED was placed. To achieve a cleaner and more adaptable design, we now custom-make the collars using grosgrain ribbon, vinyl, nylon, side release buckles, and a crocheted connector for routing wires to the hangtag interface. This approach allows for a more discreet embedding of electronics compared to the previous designs.

Updated Collar and Hangtag Design: In the latest collar fabrication workflow, nylon is precisely cut to length using a hot knife. A wooden jig, crafted with a drill press, aids in creating perfectly spaced holes corresponding to the Neopixels placement on a standard spool. The nylon is secured beneath this jig, and by pressing in a hot air gun tip, perfect circles are formed for the LEDs. Once the nylon has the necessary holes, it’s aligned with the ribbon, then a fabric pen is used to mark the location of each hole. Using a Cricut vinyl cutter, a paw print design, surrounded by a circle, is plotted; the LEDs will illuminate through the design’s negative space. The paw print vinyl is heat-pressed onto the ribbon over the LED’s exact position.

To diffuse the LEDs, given their close proximity to the ribbon, we’ve experimented with various materials. PolyGel (an acrylic powder suspended in UV curable gel, typically used for fingernails [27]) and Model Magic clay (used by Shah et al. [28] to prototype morphing robots) have shown the most promise. PolyGel offers a more smooth, diffused appearance, which, due to its suspended powder formulation, does not noticeably sacrifice luminosity, but once cured it can expose a hard edge if the nylon band bends too sharply. On the other hand, Model Magic remains somewhat soft even after drying, meaning it can flex and deform when the collar’s placement or angle is changed; however, the material’s high density can diminish the vibrancy of the Neopixels. Current deployments of the collar use a thin layer of Model Magic clay, which provides a nice, aesthetic glow⁴.

4. Design Approach

As a social robot focused on supporting therapeutic mental health interventions, Therabot™’s design is primarily guided by the needs of the therapeutic process. While

3. Details available at: <https://stars.msstate.edu/ax12acooling>

4. Details available at: <https://stars.msstate.edu/collarinterface>

the standards of clinical practice provide important design guideposts, direct engagement with a diverse group of care providers (clinicians) and care receivers (clients) through participatory design provides the nuanced design insights necessary to build a useful system. Additionally, the interdisciplinary nature of social robot development provides a continuous stream of new ideas and visions for exploration.

In this section we distill Therabot's core design goals, examine the sources that spur development, and describe the timing of events that form the overall development cycle.

4.1. Design Goals

Although the robot's development is driven primarily through participatory design and iterative cycles, four high-level design goals persist across minor and major platform changes. These goals guide the robot's primary function as a therapeutic device and shape its behavior as a social robot:

Do no harm: The robot's behaviors must recognize and abide by the ethical principles that govern the environment it inhabits. As a therapeutic device, the robot must be cognizant of medical ethics and perform in a manner that upholds these values.

In the realm of therapy a social robot occupies a space between an automated tool (e.g., a biofeedback device) and a human clinical professional. As robots in this role continue to incorporate modern developments in AI, the associated uncertainties must be carefully navigated to ensure continued satisfaction of this goal.

A sampling of critical areas related to this goal includes: maintaining privacy [10], producing a therapeutic effect in an empirically testable and accepted manner [29], understanding context and bias [11], and preventing long-term attachment [30].

Contribute to the therapeutic process: Ultimately, the robot should supply a predictable and empirically verifiable therapeutic effect that is consistent with evidence-based practice [4], [31]. At a minimum the robot should be provide value to the individual client as assessed by the clinician.

The robot should be adaptable to a variety of therapeutic orientations, cultural contexts, and treatment plans. Achieving success in this area requires extensive collaboration between developers and clinicians [12], [13]. This collaboration should leverage the expertise of each field to identify effects that may be unique to HRI in specific clinical conditions. For example, an initial investigation by Zhang et al. found that while some rewarding properties of human-human interaction were diminished for depressed individuals, the rewarding properties of human-robot interaction were less likely to be affected [32].

Demonstrate a social understanding of the world: As a physically embodied social agent, the robot

should understand the world it is situated in and attend to events appropriately. As humans are often predisposed to relate socially to robots [33], the robot should leverage these expectations to facilitate an enjoyable interaction. Furthermore, the robot should be aware of its own form and related implications. For example, the robot should produce sounds that are congruent with its physical appearance.

Adapt to diverse circumstances, needs and preferences: As a STAR, the system should adapt to the needs of the user and the context [34]. This may include adapting to environmental conditions, learning from user behavior, or using knowledge of user traits combined with prior HRI findings to optimize behavior choices. For example, Graaf et al. found that gender and prior expectations about life-likeness affected an individual's intention to treat a zoomorphic robot as a companion [35].

4.2. Design and Development Cycles

While TherabotTM's development is primarily driven by the needs of its users, these needs often traverse multiple project teams, disciplines, and design iteration cycles prior to being incorporated into the platform. In addition to user needs, development may also be initiated by system performance results, new external research findings, or the availability of new technology. Sources of development activity can be segmented into three distinct areas:

Participatory Design: The primary input signal for guiding the design of the platform is generated by PD activities that directly involve all stakeholders. These take the form of workshops and collaborative interactions between those who will use the system (e.g., clinicians, clients, etc.) and those who will implement and support the system (e.g., technical developers, social science researchers, etc.).

Studies, Trials and Performance Data: After sufficient refinement, the robotic platform is deployed in a variety of contexts from in-lab demonstrations to interactive use in design workshops to deployments with clinicians and clients. These deployments generate a wealth of data regarding how the robot performs and how that performance can be improved. The ultimate form of performance for therapeutic use is data that is generated in randomized controlled trials that use the robot as a therapeutic device.

Research and Technical Developments: Independent of design activities that include all users, technical developments that allow the robot to perform better, more efficiently, and at a lower overall cost are continuously integrated into the platform. This includes hardware developments like more accurate sensors and software developments like novel AI and ML techniques.

Currently, the project has contributors spread across four universities with one university focused on creating hardware and software (located in the Southeastern U.S.), one focused on participatory design with clinicians and clients (located in the Midwestern U.S.), and two focused on the collection of sensor data and the development of machine learning pipelines (located in Seoul, South Korea and another university in the Southeastern U.S.).

In order to prevent blocking dependencies (i.e., one team waiting on the output of another), we use a scheme of scheduling minor and major releases of the platform. This allows development of hardware and software to continue while the current iteration is used in PD activities.

Minor releases focus on development stemming from previously analyzed PD insights or as a result of performance data. These releases are designed to provide smaller improvements to the platform and are fashioned as upgrade kits that are applied to the current generation platforms as they complete their PD activities.

Major releases involve design changes that require fabrication of new hardware and include major PD insights and features that require more substantial engineering time and effort. After a major release, existing systems are returned for analysis and reuse of components in the following design cycles. This approach allows more efficient use of resources, as it assumes design feedback will be generated and processed asynchronously.

5. Ongoing Development

This section presents a snapshot of ongoing development work that will remain in progress over approximately the next year. Divided into three major categories, these activities are representative of the development goals and scope of Therabot™. Presented in the following subsections are the three development categories: (1) Participatory Design, (2) Technical Platform Development, and (3) Machine Learning and Context Understanding.

5.1. Participatory Design

Our collaborators from the R-House research team are currently analyzing data collected in a workshop, which builds upon insights from deployments of the modular sensor collar by having participants identify the behaviors that would be useful for the robot to exhibit in specific situations. Next, workshops focused on the robot's external appearance and sensors will begin in the coming months. In collaboration with researchers in the field of costume technology, prototypes of different dog and cat appearances have been developed for the robot and will soon be incorporated into studies and workshops.

In addition to workshops examining specific areas of robot use and behavior, the R-House research team continues to perform ongoing PD work with clinicians and their clients. The next important milestone in this work will involve deploying the robot into the homes of participants

for a multi-week time interval and engaging in a PD process to guide further development of the robot.

5.2. Technical Platform Development

As we aim to foster beneficial therapeutic relationships between users and the robot, the invaluable insights collected from clinicians regarding use cases and therapeutic applications for Therabot™ coupled with the principles of participatory design will play a pivotal role in steering the trajectory of our development. Recent updates to the robot introduce features such as a grid providing high spatial resolution touch sensing using capacitive fabric, adaptive heartbeat, haptic subsystem for a sense of aliveness, adaptive audio generation, and customizable user interfaces.

5.2.1. Basic Performance Improvements. Improving the robot's performance and capabilities requires an ongoing effort to integrate updated components and refine existing designs for easier fabrication. Currently efforts are underway to: upgrade the robot's smart servos to newer models, transition all custom electrical boards to PCB designs, reduce actuation sounds related to tail wagging, integrate a more powerful single board computer, transition the front microcontroller to a newer model, and test alternative joint configurations for the robot's neck.

5.2.2. Assembly and Update Kits. In addition to incorporating platform updates into the documentation and guided materials for our collaborators to fabricate additional robots, we are working to understand the best approaches to disseminating this type of information and supporting others through their fabrication processes. Insights from our first use of these materials will also help guide our future minor hardware update kits that are sent to collaborators to provide small performance updates. As more robots are actively in use it is essential that the platform is able to be maintained without the need for extensive external support.

5.2.3. Updates to Hangtag and Collar. Building upon our previous work with the sensor collar, we are in the process of designing a new iteration of Therabot's hangtag interface. The new design will incorporate sensors from the collar while offering a more user-friendly interface for the robot. Our current focus is on designing printed circuit boards (PCBs) that will integrate with an RP2040-based round 1.28 inch touchscreen LED panel with a resolution of 240x240 pixels, to serve as the hangtag interface. This significant upgrade to the user interface will allow users to interact with and control the robot in a more intuitive manner, compared to the previous three-button configuration that requires cycling through multiple pages of features. The custom PCB, as a peripheral for the RP2040, will feature a real-time clock and sensors to measure luminosity, volatile organic compounds, sound intensity, and movement. The expanded screen size and enhanced interaction capabilities provide numerous possibilities for data communication, status updates, and more refined user controls.

Of great interest to us is implementing and experimenting with a privacy mode. This mode not only allows users to determine when environmental data is collected but also offers the flexibility to enable or disable specific sensors as per their preference. To foster trust, it is essential to provide users with clear indicators about the collar’s data collection activities. For example, we plan to display the number of records collected, providing a trust cue observable by the user [36]. When a user pauses data collection, this number would be greyed out, signaling inactivity. Upon resuming, the number would become active again, reassuring the user that no additional data was collected during the pause. Such transparent communication is pivotal in reinforcing user trust [37]; furthermore, with the enhanced screen resolution, we can explore visualizations that offer meaningful insights to the user. This includes showcasing data categorization and quantities, detailing environmental attributes, presenting interaction statistics, and updating the robot’s status.

To enhance collaboration and contribute to the Human-Robot Interaction (HRI) community, the updated, sensor-integrated hangtag interface will (with minimal hardware reconfiguration) support two distinct software modes:

- 1) **Therabot Control Interface:** Here, the collar acts as an extended control interface for Therabot. It gathers and conveys environmental data to the robot via an inter-integrated circuit (I2C). Additionally, it displays aggregated environmental and interaction statistics along with other relevant information to the user.
- 2) **Standalone Mode for Zoomorphic Platforms:** In this mode, the collar operates independently when equipped with a battery module for power and an SD card for data storage. It records timestamped environmental data, which can later be correlated with ground-truth data or analyzed on its own. The collar can be attached to any zoomorphic platforms to create a smart sensing system.

5.2.4. Touch Sensing Improvements. For touch sensing improvements in Therabot™, we are focusing on two primary areas. The first is a capacitive fabric touch sensing grid and the second a photo-reflective touch sensing approach.

Capacitive Fabric Touch Sensing Grid: Over the past year we developed a soft, capacitive fabric-based touch-sensing grid (seen in Figure 6), which enables Therabot to detect thirty-three distinct “touch zones” along its back. We are also exploring other locations on the robot for the placement of capacitive touch sensing. In our implementation, the self-capacitance of each electrode is measured and analyzed. We have considered another approach, mutual capacitance. This requires a ground plane and consumes more power, but it provides greater precision. Research indicates that processing the raw capacitance values of self-capacitive electrodes arranged in a grid results in an accuracy similar to that of a mutual capacitance configuration, as reported in [38]. As a result, we are implementing a self-capacitance system, a better fit for our use case. A real-time visualization

shows activation of the sensors, arranged in columns and rows, and precisely where the robot was touched (based on concurrent sensor activations), demonstrated in Figure 7. This visualization also approximates proximity and movement direction by altering the opacity of an active sensor to correspond with its capacitance.

To create the capacitive touch grid, we adapted the electrode design presented by Wu et al. [39] by scaling their electrode design to fit optimally on Therabot™. To create our electrodes, we first used iron-on adhesive to secure the conductive fabric to a thick, insulating nylon fabric; then for cutting the final electrode shape, we used a Cricut vinyl cutter. For stability during the cutting process, the nylon side was placed against the Cricut adhesive sheet, with transfer tape applied to the conductive fabric. Once cut, we arranged the electrodes in a grid pattern and attached them to Lycra using iron-on adhesive; each electrode was aligned in rows, secured using the iron-on adhesive method. Following this, the column electrodes were attached, using the rows as alignment references. Each electrode was sewn in place on the base using conductive thread to route the trace to specific locations along the edge of the Lycra fabric where the thread connected to a conductive knit ribbon cable. This cable interfaced with a flexible protoboard adapter, transitioning into a Japan Solderless Terminal (JST) connector compatible with a plug on the MPR121 capacitive sensing breakout board. Presently, Therabot™ is equipped with a hardware mounting rack to support up to four MPR121s, enabling 48 touch sensing channels in total.

To improve reliability and durability of the touch grid, we are exploring a promising new type of conductive and insulated thread from SewIY [40]. This will enable the routing of more safely-insulated touch zones throughout the robot while maintaining the plush, padded outer feeling. Combined with connectors such as those discussed by Stanley et al. [41], our preliminary testing indicates that this thread will greatly improve the robustness of our soft, capacitive touch sensor system. Considering the insulated property of this thread, the touch-sensing grid’s granularity can be increased by implementing more complex patterns. This also opens up the possibility of embroidery or appliqué designs that allow thread to overlap itself while maintaining the integrity of the signal.

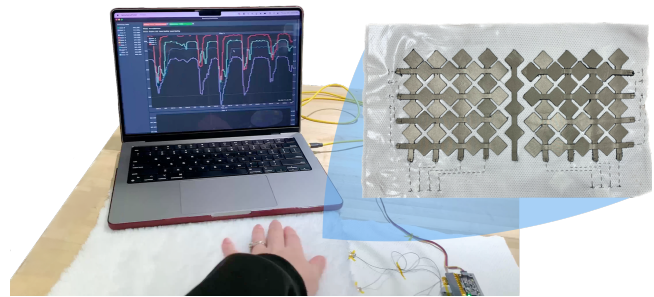


Figure 6: Testing setup for observing raw capacitance values

Photo-Reflective Touch Sensing: Though Therabot’s current capacitive touch sensing grid is made up of dif-

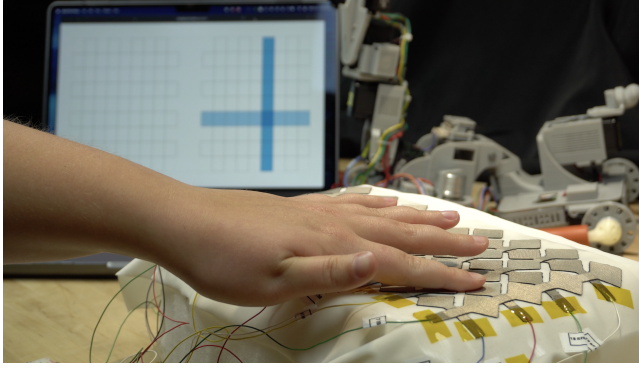


Figure 7: Capacitive grid (foreground) and real-time touch visualization (background)

ferent types of soft fabric, it can occasionally be felt when interacting with the robot, even through the covering, due to wire routing and additional fabric making up each electrode. To mitigate this side-effect, we are researching a system that uses photo-reflectivity: by affixing infrared (IR) LEDs and photo sensors to the robot’s base and a photo-reflective fabric to the inside of the covering, changes to the density of the padding can be approximated by measuring reflectivity across multiple photo sensors. This would allow the location and magnitude of touches to be distinguished in a manner similar to the interfaces examined in SofTouch [42] and FuwaFuwa [43]. This would reduce the need to route wiring or sew additional fabric sections near the outer surface of the robot.

5.2.5. Ultra-Wideband (UWB) Radar Sensing. Extending beyond the capacitive touch grid, we are also exploring an additional sensing approach to allow understanding a user’s physical interactions with the robot, as well as to gain an understanding of the spatial location of people and objects within its immediate environment.

Most living creatures use multiple senses (e.g., vision, hearing, etc.) to maintain awareness of their surroundings. For example, a pet dog may orient toward people that it sees entering its environment or may respond to hearing its name. While the robot is able to sense touch events and basic sound levels within the environment, it currently lacks the abilities that are traditionally served by a vision system. While sound localization can provide some awareness of the scene that surrounds it, the robot’s current sensors do not empower it to understand at the level of fidelity that would be expected of an actual animal.

Although the addition of traditional cameras and a vision processing pipeline would enable the robot to attend to its environment in a more responsive manner, we have not incorporated this into the robot as it affects the actual and perceived privacy of those using the system. Our design process is ongoing and based on discussions with participants, we have noted their desire for strong privacy assurances. Many users have expressed appreciation for the system’s lack of cameras.

To help balance user privacy with the robot’s need to understand its surroundings, we plan to investigate the use of emerging techniques that use UWB radar to facilitate reliable person and activity detection. Early efforts using this approach to monitor patients in assisted living facilities while maintaining privacy have shown promising results [44], [45]. However, incorporating the necessary hardware into the robot’s form factor is not trivial. Overall the development of more privacy-sensitive techniques for sensing is a pursuit that could greatly widen the acceptance of robots in particular domains, especially related to companion robots.

5.2.6. Adaptive Heartbeat and Haptics. To improve the perceived haptic feedback of its simulated heartbeat, we are testing the use of small eccentric rotating mass (ERM) vibration motors that are able to support a wide range of haptic outputs [46] [47]. This approach may also allow better simulation of general aliveness as well as creature specific behaviors, like purring in a cat form factor.

In an effort to explore the therapeutic potential of responsiveness through haptic feedback, Therabot™’s heartbeat functionality has been expanded to include adaptive behaviors. When connected to a compatible physiological sensor, such as EmotiBit [48], the robot is able to wirelessly receive and respond to a user’s heart rate by matching its simulated heart rate to the heart rate of the user. Using the user’s heart rate data, Therabot™ is also able to recognize and respond to physiological states that indicate distress. The robot’s response to potential distress is to slow its simulated heart rate, with the intention of portraying a calmed state and inducing a positive physiological response from the user. The current thresholds for normal and distressed user heart rates are based on the ranges of a typical adult heart rate [49], but we aim to create a truly adaptive heart rate that can accurately identify distress in users with elevated heart rate ranges. Although currently the adaptive nature of the heartbeat only responds to distress found in live physiological data, alternative methods for sensing distress, such as detecting affect through touch and gestures, are feasible. In the future, we plan to implement additional adaptive behaviors, beyond the slowed heart rate behavior, that will contribute to the responsiveness of Therabot™ as a whole. These could include movements, sounds, or other calming behaviors exhibited by the robot to calm a user.

5.2.7. Audio Generation. In an effort to provide further customization options for Therabot™, its audio production system has been expanded to facilitate the generation of more natural and user-aligned sounds. While the system previously selected audio from a library of audio clips, novel sounds are now generated by the robot based on a number of specified sampling parameters. We are currently conducting studies examining the ability to convey emotions through augmentation of sound generation parameters. Our initial implementation, focused on the robot’s dog form-factor, makes use of pitch and spacing adjustment parameters adapted from dog bark analyses performed by Pongrácz and Molnár in 2005 [50].

Given Therabot™’s primary function as an in-home therapeutic companion, the generation of novel and distinct audio is not merely an enhancement but a necessity. To shift away from procedural audio, a generative flow model like the one presented by Andreu and Aylagas, proven to successfully generate explosion sound effects, would serve as an ideal paradigm for unique audio creation [51]. A custom dataset of approximately one hundred labeled audio clips would be sufficient to train a model capable of generating complex and variable audio samples. While our initial efforts have been concentrated on Therabot™’s canine form-factor, if trained on a variety of video game and fantasy sounds, the user could describe their creature’s sound profile. The model could then apply it, when generating audio, to the appropriate cadence to communicate a desired emotion [52].

5.2.8. Software: interfaces and architecture. In conjunction with ongoing participatory design work, customizable software interfaces and mobile apps are being developed for both clinicians and their clients. In contrast to the existing system development and research-oriented interfaces, these interfaces are tailored to the individual contexts of their specific users. Alongside these visible developments, the internal software architecture that regulates the robot’s behavior continues to be refined and further developed. As part of this refinement, geofencing is being considered for inclusion in the interfaces and apps to awaken Therabot™ to greet the user when they arrive home.

5.3. Machine Learning and Context Understanding

Our collaborators in Dr. Bennett’s lab at Hanyang University are currently fabricating a Therabot™ platform that will be used to test the deployment of deep learning models onboard the robot. Sensor models developed from data collected with the modular sensor collar will be used to allow the robot to understand its context. Contexts will be linked with behaviors developed in participatory design workshops and integrated into the robot’s control architecture to assist in shaping its autonomous behaviors.

6. Future Development

As we envision Therabot™’s development trajectory over the next five years, four crucial areas of development emerge: clinically focused design, privacy-oriented sensing, AI within participatory design, and broadening interfaces. In this section we describe the importance of each area as they relate to Therabot’s overall design goals.

6.1. Clinically Focused Design and Validation

The integration of social robots into mental healthcare presents a vast landscape of questions regarding effectiveness, ethics concerns, and societal implications [11], [12], [13], [53], [54], [55]. While our expertise is in human-robot interaction, clinicians and clinical practice guide our efforts.

As a useful therapeutic robot cannot exist without strong collaborations between these fields, we believe continued partnerships between all stakeholders are essential [13]. We plan to continue close collaborations with clinical professionals and their clients indefinitely.

While researching, building, and evaluating social robots for therapeutic uses continues to advance with promising results, most efforts to date stop short of the rigorous randomized controlled trials (RCTs) that are used to evaluate clinical treatments (several recent exceptions exist [3], [7]). Over the next five years of development we aspire to evaluate Therabot via RCTs.

Separate from the direct social interactions that occur as part of therapies using social robots, the ability of these devices and other popular consumer electronics (e.g., smart watches, fitness bands, smart homes) to collect extensive data related to health is a promising area for further inquiry. We are early in our investigations into the uses of sensor data collected with Therabot [25], but plan to continue working with clinicians and clients to understand how this data can be leveraged in an ethical and beneficial manner.

6.2. Optimizing Privacy-oriented sensing

As privacy and user perceptions of privacy are among the most critical design elements of a social robot used in mental healthcare, we foresee substantial value in continued efforts to further develop this area.

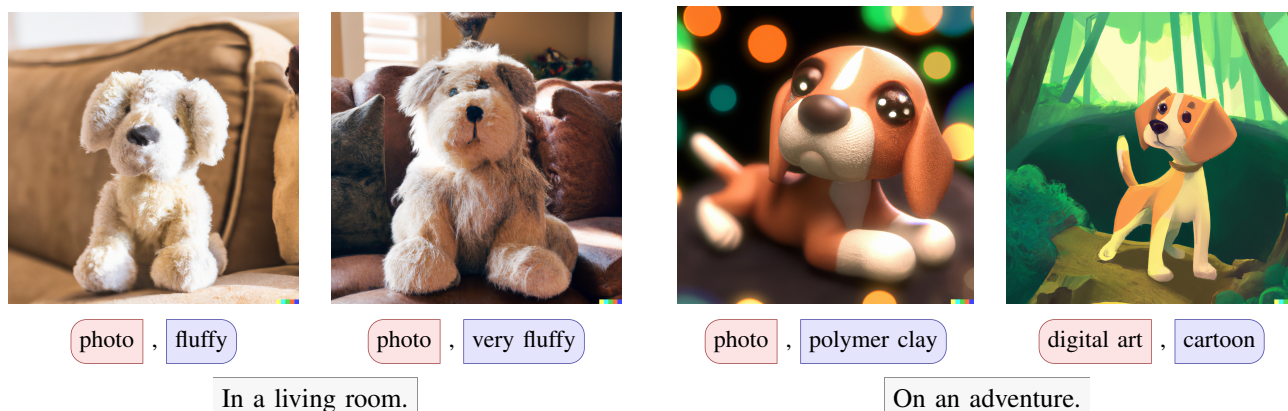
Moving forward, we plan to develop both strong technical assurances of user privacy and investigate interfaces and design conventions that align user perceptions with the true state of the system. Within the realm of mental health care the therapeutic alliance between clinicians and clients is pivotal to enabling meaningful change. We will continue to work with clinicians directly to design a system that provides information that enables clinicians and clients to decide how the robot should be used in their therapy.

Our engineering efforts will continue to emphasize the requirement of local on-device data processing and strong physical and digital security. We will continue to refine our sensor systems to collect the data necessary by default. For example, we will pursue technologies like ultra wide band radar for person detection rather than RGB cameras as a means of protecting privacy [56]. Contextual understand will be provided by using sensor fusion techniques with several low fidelity data streams.

Furthermore, we will work to develop mechanisms that allow the user to be assured each sensor is physically disconnected when desired. Alongside these features, we will endeavor to provide interfaces that allow a user to easily review and delete any data the system has stored.

6.3. Incorporating AI into the Participatory Design Process

Artificial intelligence presents a revolutionary opportunity for participatory design. With the capabilities of



Realistic, depicted in home environment

Stylized, showcasing personality

Figure 8: {type of image} of a cute {aspect of subject} stuffed beagle puppy {activity}

generative AI in the PD context, researchers can delve deeper with design study participants by quickly creating a high fidelity image of the participant’s described support companion. After generating an initial design, the researcher and participants can use the generated artifacts to refer to specific features and elicit details that might have previously required multiple PD cycles. In this paradigm the generative artificial intelligence process may also become a contributor of important novelty as it may produce design elements that the participant or researcher did not consider.

In the realm of participatory design for social robots, there are vast design possibilities with a platform like Therabot™, which uses an external covering that can easily be changed or redesigned independent of the robot’s functionality. Another consideration for the PD process is whether participants would prefer to create their robot’s character in a 3D format, resulting in a more realistic representation true to the robot design, or opt for two-dimensional, stylized versions. Furthermore, designs may begin as a more realistic image with adjustments made to specific features, or they may begin in a stylized cartoon-like image, capturing the personality and key features demonstrated in the digital art. As illustrated in Figure 8, generated by DALL-E 2⁵, realistic images offer a glimpse of the potential robot inhabiting a more true-to-life form factor and placement. A wide variety of customizations can be made to facilitate discussion and discoverability; the images “In a living room.” demonstrate the addition of the word “very” in the prompt: “a photo of a cute [very] fluffy stuffed beagle puppy in a living room.” The images depicting the robot “On an adventure” explore stylized and character-focused versions of the prompt. While the two-dimensional representation may not translate perfectly to the stuffed animal dimensions, the real-life Therabot covering would still capture the main design features requested by the participant. As a result of advances in generative AI, creating a participant’s ideal socially therapeutic assistive

robot starting from a design concept and then creating a custom covering has become a more viable possibility. Beyond visual design, Therabot could adapt to any animal type by generating audio in real-time using a text-to-audio latent diffusion model such as AudioLDM [57] to mimic the participant’s chosen animal. Combining a customized appearance and sound profile with Therabot’s contextual awareness to adapt behaviors, would enable participants to more rapidly experience their design choices. This pipeline may also be extended using the generated images to teach a character-focused model like Dreambooth [58] to enable easy asset generation for a virtual version of the robot. This would allow participants to engage with a virtual version of their customized companion through an app, embarking on adventures, achieving self- or clinician-guided goals, or playing games.

6.4. Broadening Interfaces

Extended Reality (XR) modalities have the potential to be powerful tools for improving mental health conditions. A review by Ma et al. found that more immersive environments tended to be more effective for mindfulness training [59]. Engaging more senses, such as touch, has the potential to augment the immersive environment in a beneficial way [60]. A study conducted by Lin et al. explored immersing participants in environments with virtual pets, followed by a discussion of the experience [61]. Their reporting on virtual pets provides important insights for the Therabot™ project. Participants hoped to build relationships with the virtual pet and highlighted the importance of the virtual pet initiating interactions. They felt that for a meaningful connection, the virtual pet should exhibit an awareness of its environment and appropriately respond to it. For instance, just as a real dog responds to its owner’s emotional prosody, a virtual pet should do the same. They also suggested virtual pets learning new tricks and showcasing a long-term understanding would facilitate the relationship. A significant point of

5. Available at: <https://openai.com/dall-e-2>

interest was the desire of participants to physically touch the virtual pet.

Therabot, being an embodied agent, meets many of these needs, and its integration with an XR paradigm has the potential to create a meaningful immersive experience. Using its integrated sensors, the robot could supply virtual elements with useful signals, like detecting when a user is nearby to cue the reaction of excitement, inviting engagement. Adding the data from UWB radar and capacitive sensors, the robot can gauge as a user approaches and touches it, perhaps scaling down movements that were broad to elicit attention from the user. Diffusion models can be leveraged to generate custom virtual assets, allowing users to experience an interactive extended reality with their chosen Therabot. By utilizing local network connections, Bluetooth, or alternative technologies such as audio cues, actions in the virtual space can prompt responses from the physical robot. This offers users a tangible Therabot that responds to virtual interactions.

Therabot™ has been an evolutionary design and development process ongoing since its inception in 2012. With so many possible future directions, it is expected that this evolutionary process will continue for the foreseeable future. Our eventual goal is to make Therabot more widely available to developers and eventually for clinician and public use.

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