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Designing Vyo, a Robotic Smart Home Assistant: Bridging the Gap Between Device and Social Agent

Michal Luria Guy Hoffman Benny Megidish Oren Zuckerman Sung Park

Abstract— **We describe the design process of "Vyo", a personal assistant serving as a centralized interface for smart home devices. Building on the concepts of ubiquitous and engaging computing in the domestic environment, we identified five design goals for the home robot: engaging, unobtrusive, device-like, respectful, and reassuring. These goals led our design process, which included simultaneous iterative development of the robot's morphology, nonverbal behavior and interaction schemas. We continued with user-centered design research using puppet prototypes of the robot to assess and refine our design choices. The resulting robot, Vyo, straddles the boundary between a monitoring device and a socially expressive agent, and presents a number of novel design outcomes: The combination of TUI "phicons" with social robotics; gesture-related screen exposure; and a non-anthropomorphic monocular expressive face. We discuss how our design goals are expressed in the elements of the robot's final design.**

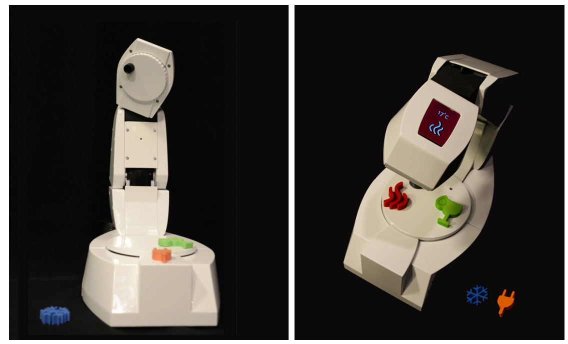

Fig. 1. Vyo, a personal robot serving as a centralized interface to smart home devices. The microscope-like robot transitions between being a social agent communicating with the user (left) and an inspection device used as a tool (right). 3D-printed icons represent smart home devices and are placed on the robot's turntable to activate devices and to control their settings.

I. Introduction

Devices with new sensing and monitoring capabilities are entering the home, often collectively called "Smart Home" or "Internet of Things" (IoT) devices [1]. Researchers have been divided over the desired user experience of these devices. Conceptual frameworks range from high system autonomy and invisibility on the one hand [2], [3], [4], to technology that promotes the user's sense of control and engagement on the other [5], [6].

Social robots are also increasingly entering the domestic environment. As such, they could provide a new model for the "smart home" user experience, balancing autonomy and engagement. In this paper we describe the design process of such a robotic smart home interface.

Based on the research literature, user interviews, and expert input, we define five design goals as guidelines: engaging, unobtrusive, device-like, respectful, and reassuring. We then describe our process leading to the construction of a new socially expressive smart home robot, Vyo. The process simultaneously and iteratively tackles the robot's morphology, nonverbal behavior (NVB) and interaction schemas.

The final prototype is a large microscope-like desktop robot (Fig. 1) capable of social gestures. Users communicate with it using tangible objects ("phicons") placed on a turntable at the robot's base. Each phicon represents one smart home device, and is used to turn the device on and off, to get information on its status, and to control its parameters. The robot also features a screen, exposed to the user via an expressive bowing gesture when a phicon is detected. In this interaction schema the user looks "through" the robot's head into the information represented by the phicon, treating the robot as an inspection tool. When a device requires the user's attention, the robot alerts them using unobtrusive gestures, following the principle of "Peripheral Robotics" [7].

M. Luria, G. Hoffman, B. Megidish and O. Zuckerman are with the Media Innovation Lab, IDC Herzliya, P.O. Box 167, Herzliya 46150, Israel michal.luria@idc.ac.il

G. Hoffman is with the Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY 14853, USA hoffman@cornell.edu

S. Park is with Sk Telecom, Euljiro 2-ga, Jung-gu, Seoul, 100-999, Republic of Korea spica7601@partner.sk.com

II. Related Work

A. Smart Homes

Homes are becoming increasingly "smart" by being equipped with new sensors and monitors [1]. This raises a question on the way these smart homes should be controlled. Weiser envisioned the future of domestic technology to be calm, ubiquitous, autonomous, and transparent [2], an idea later supported by other researchers [4], [3]. However, this notion generates an "automation invisibility" problem, where users could lose the sense of control over their domestic environment [8]. In contrast, other notions on intelligent environments suggest that technology should *engage* people rather than soothe them. Rogers, in particular, argues for a shift from proactive computing to proactive people [6].

In most cases, these "smart homes" are envisioned as a single interconnected unit [9]. In reality we find a host of unrelated, separately controlled devices. Research attempting to solve this problem spans a variety of interface modalities, including voice recognition [10], screen-based interfaces [11], gesture control [12] and tangible objects [13]. In this work, we suggest a social robot as a central interface for smart home management.

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B. Social Robotics in Smart Homes

In the past years social robots emerge beyond the laboratory into personal spaces. This trend is likely to grow, as many people are in favor of robotic companions accompanying their domestic lives [14]. In this work we propose using them as an interface for integrated smart home control.

Previous research explored the idea of a social robot as part of the smart home [15], [16]. However, these works focus on assistive technology for the elderly rather than smart home management for the general public, as suggested here.

In particular, we present the design of a new social robot as a centralized interface for smart homes, combining principles of robotic expressiveness and interaction with tangible objects.

C. HRI Design Techniques

Academic research on social robot design has proposed a variety of methods and techniques. These can be categorized as addressing three interrelated aspects of HRI:

Some work relates to designing robotic *nonverbal behaviors* (*NVB*). These include embodied improvisation [17], animation studies [18], [19] and observation of human-human interactions [20].

Other methods are considered for designing *morphologies*. These include surveys, rapid prototyping, and laboratory studies exploring and evaluating the robot's body dimensions [21], proportions [22] and facial features [23].

Finally the *interaction schemas* of the robot have been designed using methodologies taken from HCI research, such as interviews [24], ethnographies [25], storyboarding [26], and interaction experience mapping [27].

In this work, we emphasize the interrelatedness between the robot's morphology, NVB, and interaction schemas using a simultaneous iterative design process, which goes back and forth between these three design channels.

III. Design Goals

We identified five design goals, based on prior research in ubiquitous computing, engaging technologies, and domestic robots. These were further informed by interviews with users about their needs and desires of smart home interfaces [28].

A. Engaging

A smart home interface should promote the user's sense of connection with their domestic environment. This sense can be evoked by engaging the user and bringing back "excitement of interaction" [6]. According to Rogers, one way to engage the user would be to design for a physical-digital experience, a tangible user interface.

B. Unobtrusive

Previous research, expert input from industry, and our own user interviews all suggested that domestic technology should be at least semi-automated, aspiring to as few disruptions as possible. This would allow people to focus on developing close relationships within their family [29], [4]. Thus, our second design goal is to design a robot that will draw attention only when it is essential. Of course there exists tension between this and the "engaging" goal, and the design should strive to balance the two.

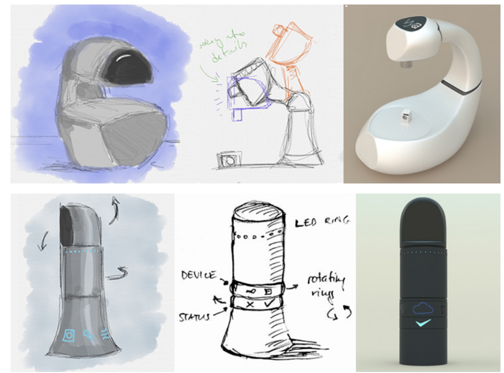

Fig. 2. Morphology sketches and high-fidelity 3D models of two concepts: Expressive Appliance (top) and Consumer Electronics (bottom).

C. Device-like

Most domestic robot designs see the robot primarily as a social agent, often with humanoid or anthropomorphic form. Following the arguments for "Designing Non-Anthropomorphic Robots" in [18], we aim for a more device-like domestic robot design, striking a fine balance between device and social agent.

This point is also supported by [14], where participants preferred a home robot characterized as a "butler-like" assistant (79%) or as an appliance (71%). Only few wanted a home robot to be their friend or mate.

D. Respectful

According to the butler-like preference described in [14], people expect the robot to have "etiquette", "politeness", and "sensitivity to social situations". For example, a butler is expected to sense when it is suitable to actively alert their employer, as opposed to when to step aside and wait until given further orders. We therefore suggest robotic assistants should evoke a sense of *respect* towards their "employer".

E. Reassuring

Finally, our interviews, as well as [14], strongly suggested people need the domestic robot to be reliable, reassuring, and trustworthy. This cannot rely solely on fault-tolerance [30], but should also be embodied in the design of the robot's morphology, NVB, and interaction schemas.

IV. Design Process

To achieve these design goals, we collaborated with an interdisciplinary team from the fields of behavioral science, design, and engineering, together with practitioners in movement-related arts (actors, animators and puppeteers).

Our design process started with the simultaneous and iterative development of the robot's morphology and nonverbal behavior (NVB). Both paths continuously defined and refined the robot's interaction schemas. These three aspects were evaluated in a user-centered design study using a puppet version of the robot, leading to the final prototype design.

A. Morphology

The design of the robot's morphology followed an iterative process involving sketching, 3D modeling, and rapid prototyping, inspired by the movement-centric design approach introduced in [18] and elaborated in [7]. Our design process went beyond the work described in these papers in two ways: First, in previous work, alternatives were considered only in the early sketch stage. Here, we simultaneously developed two options to an advanced design stage, including sketching, 3D modeling, and animation testing (Fig. 2). Second, we built and rendered a high-fidelity 3D model (Fig. 2 right), which was iteratively interleaved with the sketching and 3D animation phases. Through it we explored materials, morphological accents, and finishing details at an early stage.

The following sections describe the considerations, steps, and decisions made in the morphology design stage.

1) Sketching: We started with freehand sketches exploring widely varying shapes based on real-world inspirations. Supporting the "device-like" design goal, we did not want the robot to have human features, but to be more of a socially expressive household device. We thus started two designs paths, which we called Consumer Electronics (CE) and Expressive Appliance (EA).

On the CE path, we aimed for a minimal design that would be familiar as a high-end consumer electronics object. This resulted in simple shapes, expressing most of the user feedback through LED lighting and graphical information. In fact, we decided that any physical motion would not affect the envelope of the robot, but only rotate elements along the major axis of the robot (Fig. 2 bottom center). Inspirations for this robot's design were contemporary bluetooth speakers, Amazon's voice interface device "Echo", and—for major-axis rotation—the fictional robot R2D2.

On the EA path, sketches focused around appliance morphologies. Fig. 2 (top left) shows some early sketches, mostly following a kitchen mixer / microscope / overhead projector theme, with some diverging towards designs inspired by wall-mounted displays and even clothes hangers (not shown).

Some key morphology and interaction ideas related to our design goals emerged at the sketching stage: (a) straight envelope lines—related to the *device-like* goal; (b) tangible icons ("phicons") representing the devices managed by the robot—related to the *engaging* and *reassuring* goals; (c) a "bowing" gesture, which exposes a hidden head-embedded screen presenting additional information—related to the *respectful* and *unobtrusive* goals. The last design idea also placed the robot on a midpoint between an inspection device and a social agent. When the robot would rise to face the user, it would be a social agent. When it would bow, it will become more passive and will enable the user to "look through" its head like a microscope, examining the status of the smart home devices. This had the additional engaging aspect of "peeking into the robot's mind."

As the sketches evolved, the microscope became an increasingly salient inspiration. As a result, we included a rotating face plate with a lens-like feature that would serve as an expressive element in the robot's face design. The one DoF lens-like "eye" placed off the face plate's center of rotation (see: Fig. 6 left) became an intriguing face design, evoking both seriousness in inspecting the home device's phicons, but also expressing a surprising range of facial expressions through movement.

2) Material: Since the robot is intended to be a household object, we wanted the material to reflect appropriate qualities. Each of the two design paths was assigned its own materiality. The EA path followed a nostalgic path, including white enamel or Bakelite, with brass or gold accents, found often in traditional household items. The CE path was designed with more of a contemporary material in mind, such as matte plastic or black anodized aluminum.

3) Rapid Prototyping of Low-fidelity Prototypes: Another extension relative to our previous design process was the use of several variations of low-fidelity prototypes. In our previous work, we used a single wooden prototype to start developing software on [31], [18]. In this case, we used rapid prototyping techniques to develop variations of the robot in low-fidelity "puppet" versions that could be moved manually, structured according to the robot's DoFs. This was not only for early software development, but also to explore various robot scales and to experience the DoFs as they moved in space. Furthermore, we used these variations in the movement simulations with a puppeteer, and in the user-centered design studies discussed in Sections IV-B and V.

B. Nonverbal Behavior

In parallel to working on the robot's morphology, we developed its movement and behavior. For this, we collaborated with experts in movement-related arts (animators, actors and a puppeteer), using the above-mentioned low-fidelity prototypes.

1) Animation Sketches: Animation sketches along the line of [18] explored the relationships between the robot's parts. In particular we wanted to explore how the placement and angle of the various DoFs would affect the robot's expressive capabilities. Fig. 3 shows filmstrip stills from this stage of the design. The animation sketches also helped us determine the relative sizes between the robot's parts.

2) Embodied Improvisations: Working with professional actors, we carried out embodied improvisations in the spirit of [17]. Each improvisation included two actors who were asked to act out situations between a butler and a tenant. This was a metaphor for the human-robot interaction we aimed for. We used improvisations to learn about nuances in a butler-tenant relationship, later implementing them in the robot's behavioral patterns. One of the findings was the particular unobtrusive nonverbal behavior of the "butlers". This sparked the idea to give the robot a number of peripheral notification gestures, which would be expressed using subtle changes in its normal idle behavior. Another behavioral pattern we found was that the butlers were constantly attentive and alert when the tenant was nearby.

3) Movement Simulations: We conducted movement simulations with a professional puppet designer, an expert in

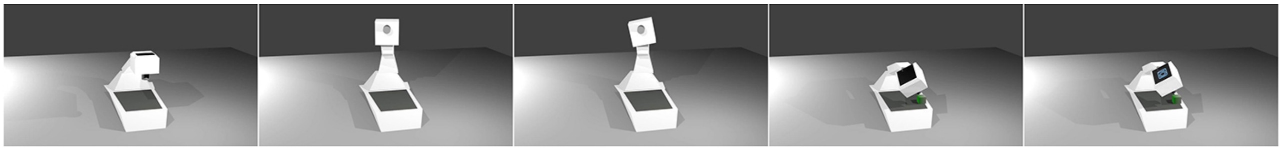

Fig. 3. Animation sketches used to explore the robot's movement, DoF placements, and expression capabilities.

movement and NVB. We used the low-fidelity puppet prototypes of the robot to explore possible expressions, gestures and responses in key scenarios. The designed behaviors were later tested in the user-centered design studies (see Section V).

4) Physical DoF Explorations: Finally, we 3D printed a variety of angled connectors and head models to compare the sense we gleaned from the animation sketches, when facing the robot in reality. We compared the expressive capability of various lengths of DoFs and different angles between them. These were then integrated in the robot's low-fidelity prototypes and animated for comparison.

V. User-Centered Design Studies

After developing the robot's morphology and NVB and before constructing the final prototype, we conducted user-centered design studies using puppet versions of the robot. We did this to simulate a variety of possible scenarios and robot behaviors, akin to the methods presented in [17], [18]. The study aimed for early stage evaluation with potential users in the spirit of paper prototyping [32]. The study set out to evaluate the robot's morphology, NVB, and interaction schemas, and in particular to get a sense of the way the robot's personality is perceived before finalizing the design.

A. Procedure

We recruited a sample of seven students to participate in the study (3 female, 4 male). Participants were Communication and Computer Science undergraduate students unfamiliar with the project and its goals. We recruited participants from our target population. All participants were over the age of 23 (M=27) and manage their own household. The small sample would serve as a preliminary assessment of the robot design, partway along the process.

We used three low-fidelity versions of the robot, two of them puppets with full articulation of the robot's movement according to its DoFs (Fig. 4 left). The study was held in an experiment room with controlled lighting, no windows, and two recording video cameras. The users were informed of the robot's general purpose: a robot serving as a centralized smart home management interface.

The study included qualitative assessment through semi-structured interviews and a quantitative part conducted with the help of a "Personality Meter", a hand-sized box with five linear slide potentiometers. Each slider was assigned to a perceived personality trait: responsibility, attentiveness, politeness, professionalism and friendliness (Fig. 4 left). This tool allowed participants a quick relative evaluation of the robot along several measures at once.

We evaluated the three aspects of our design process:

1) Morphology / Size: The robot was introduced to the participants in three different sizes (33cm, 25cm, and 21cm tall) and in slightly different forms. Participants were asked to evaluate each size on the "Personality Meter".

2) NVB / Gestures: We defined two or three optional gestures for each behavior (e.g., "listening", "getting attention" and "accepting request"). The gestures were based on the movement simulations conducted with the puppet designer. The experimenter was trained in advance to accurately and consistently puppeteer the robot's defined gestures. Each gesture was evaluated in both qualitative and quantitative measures: first the participants were asked to identify the meaning of each gesture (qualitative) and then they were asked to evaluate it using the "Personality Meter", addressing the five personality traits (quantitative).

3) Interaction Schemas / Phicons: Two forms of objects were given to the participants for a qualitative evaluation: 3D printed phicons and cubes (Fig. 4 right). The procedure was gradual revelation: At first the participants were asked what they thought the objects were; then they were told the objects are a tool to communicate with the robot; next, that each object represents a smart home device, and so on.

B. Results

In the quantitative part of the study, each "Personality Meter" sample was coded using digital images of the meter, and put on a scale of 1-5. As there were relatively few participants ($n = 7$) we present the results in overview and graphical form. The qualitative semi-structured interviews were video recorded and transcribed. We analyzed the transcripts to identify recurrent themes.

1) Morphology / Size: When analyzing the quantitative data, we found the largest robot was rated highest on all five personality measures, with a trend showing that the smaller the robot was, the lower it was rated (Fig. 5). The qualitative findings also supported this conclusion. In the

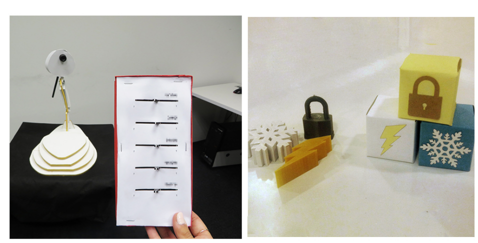

Fig. 4. Design studies using puppet prototypes with a "Personality Meter" (left), and two forms of TUI objects: "phicons" and cubes (right).

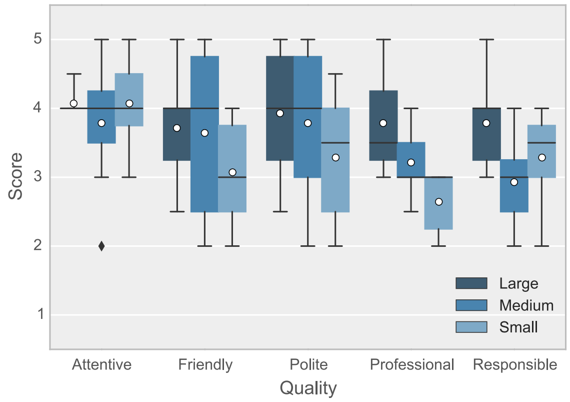

Fig. 5. Evaluation of the robot's size according to five personality traits. Box plots show quartiles, white dots show means.

interviews, the largest robot (33cm tall) was described as more reliable, professional and responsible. As both methods of the evaluation indicated the large robot is perceived more positively, we designed the final prototype to be close to its large scale version.

2) NVB / Gestures: When comparing two or three different gestures for a specific behavior, we were surprised to find that most participants rated one of the gestures higher across all personality traits. This was in contrast to our expectations for a trade-off between characteristics for each gesture. For instance, a gesture of the robot leaning in and slightly turning its head as an expression of "listening" was better evaluated than the robot rolling its head to express the same action, on all five parameters. This could be due to the fact that participants had difficulty separating the character traits, or that people generally converge to a "winner-takes-all" mentality. The qualitative interviews also suggested that the meaning of the preferred gestures was better understood by participants. This allowed us to easily choose the robot's gestures for each planned behavior.

3) Interaction Schemas / Phicons: Most participants understood the physical objects were a form of communication with the robot, each representing a smart device. Some participants perceived the robot's turntable as an affordance indicating the objects should be placed on top of it to interact. Others needed further explanation. We did not find a clear preference to one of the two object forms, but similar advantages and disadvantages were pointed out in the qualitative study: the phicons were perceived as playful and innovative but also easy to lose. Conversely, the cubes were described as unified and simple to store.

VI. Final Prototype

According to our initial design goals and considering the findings in our design exploration and research, we developed the fully functional robot prototype, including its structure, shell, electronics, and software. The robot includes 5 DoFs: One at the bottom of the turntable, one for base tilt, one neck tilt, one combined neck pan and roll, and a monocular rotating face (Fig. 1 and 6).

The robot is a microscope-inspired, Bakelite-like finished robot, that communicates with the user using tangible icons (phicons). Each phicon represents a smart home device, allowing the user to control and monitor it by placing it onto the robot's rotating turntable. Moving the phicon controls the parameters of the device (Fig. 6 right). Furthermore, the robot features a hidden screen on the back of its head, exposed through a respectful "bowing" gesture. The screen serves to give more information about devices, and as visual feedback to the user's actions. The user can "look through" the robot's head at the information represented by the phicon.

The interaction is complemented by expressive gestures using the robot's five degrees of freedom. These include the rotating monocular facial expression system mentioned above (Fig. 6 left).

The robot's main controller is a Raspberry Pi 2 Model B running a combination of Java and Python code. In addition, it includes a camera to detect phicons and faces, a 1.8-inch TFT display, and a speaker for sound output. The DoFs are driven by a combination of Dynamixel MX-64, MX-28, and XT-320 motors, controlled from the Raspberry Pi GPIO. The robot's shell is 3D printed, and externally finished with five layers of paint and sanding.

VII. Relation to Design Goals

Our design goals were embodied in the final prototype as follows:

A. Engaging

To encourage engagement in interaction with the robot, we used physical icons to control smart home appliances. The metaphor that inspired our design was that of a microscope: the user actively examines the status of a device by placing its phicon on the turntable. The user then peeks into the robot's head and "reads its mind" onto the information about a specific device. Previous research shows tangible objects have the potential to increase playfulness and exploration [33], [34]. We believe that the use of physical objects in our design can also support this kind of engagement. According to initial findings in our study, participants perceived the phicons as playful, due to their color and form.

B. Unobtrusive

To balance this playful engagement with respect for the human relationships in the home, we designed the interaction using the "Peripheral Robotics" paradigm [7], avoiding interruptions unless there is a critical matter, and generally waiting for the user to initiate interaction. We designed several peripheral gestures to replace traditional notifications used in home appliances. Since the robot is part of the domestic environment, we assume that its regular gestures will be well recognized by the user and fade into the background after a while. This allows design of subtle changes in the robot's movement, indicating unexpected occurrences. For example, a nervous breathing gesture was designed to cue there is a non-urgent matter to attend to, one that can be ignored by the user if they are busy. A second movement pattern, "urgent

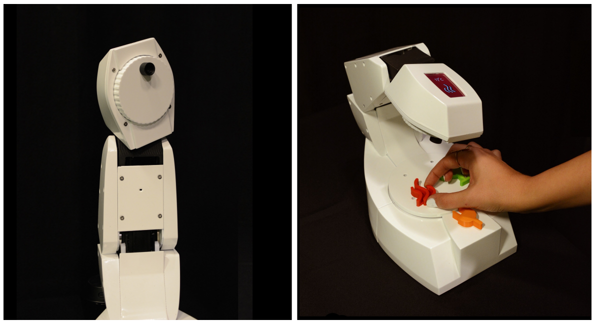

Fig. 6. The resulting prototype, including a rotating monocular facial expression system (left) and "phicons" to control and monitor smart home devices (right).

panic", was designed to move the robot from the periphery of the user's attention to the foreground.

The use of phicons also supports unobtrusive interaction, compared to using a screen, making control quiet and domestic. This is inspired by minor rituals people do in their homes—hanging a coat, placing keys in a bowl [35]. We used this idea as a metaphor—a person can place phicons on the robot's surface to set their home preferences just as easily as they would place keys on the counter. Furthermore, if the preferences are constant, a glance toward the robot's turntable enables a quick status update.

C. *Device-like*

We attempted to balance between the "social agent" and "device-like" qualities of the robot. In its "down" state, the robot is structured to resemble a device and encourages seeing it as a passive tool. In contrast, when greeting the user or when accepting a command, the robot rises up and serves as a social agent. This is supported by our qualitative findings—usually when the robot rose to look at the participant, the participant would look directly at the robot's face. However, when the robot was in its "down" state, the participant would be focused on the turntable and phicons.

This balance is also emphasized in its physical design—the robot is angular from a lateral view, and more rounded when viewed from the front.

D. *Respectful*

The respectful characteristic was inspired by the "butler" metaphor, and was amplified by the actors' embodied improvisations playing out the role of a human butler.

We express respectfulness in the design by rising to the user's *attention* when they are within the robot's range. For instance, when the user enters their home, the robot responds with a greeting gesture, signaling it acknowledges their arrival. The user can choose to respond to the robot, or to ignore it, in which case the robot would "go back to its own business". Furthermore, whenever the user passes by the robot, the robot notices them and responds in a slight acknowledgment gesture. These decisions stem from our observations on human interactions played out by professional actors—when the butlers were trying to act out "respect", they were attentive as long as the tenant was around.

An additional way in which the robot expresses respect towards the user is by employing "bowing-like" gestures.

E. *Reassuring*

In the design research we found the robot was perceived as most reliable and authoritative in its largest form. Therefore, we designed the robot in a size similar to the size of the large puppet prototype.

We also designed expressive gestures to give *feedback* to the user on their home status. For instance, when the user places an object, the robot responds immediately by examining it. Another way the user can be reassured is through the screen on the robot's head. The screen displays the icon that is currently manipulated, coherent in both icon form and color to the physical icon on the turntable. Moving a phicon gives immediate feedback on the newly set parameters. The physical icons also enhance the *visibility* of the smart appliances being monitored. They can be instantly observed with a cursory glance, contributing to the user's sense of control over their home.

VIII. Conclusion and Future Work

Domestic robots are an attractive candidate for integrated smart-home interaction, providing an alternative to the more common screen-based and voice-based interfaces. Based on prior research in domestic interaction and our own interviews of potential users, we identified five design goals for smart home robotic assistants: engaging, unobtrusive, device-like, respectful, and reassuring. We reported on our iterative design process, addressing the three core HRI design paths: morphology, nonverbal behavior, and interaction schemas, which we explored in an interleaved manner. Our process also brought together a broad range of design techniques including sketching, animation, material exploration, embodied improvisations and movement simulations.

The outcome of our design process is *Vyo*, a socially expressive personal assistant serving as a centralized interface to smart home devices. Our design goals are expressed in the final prototype: (a) *Engaging*—physical objects represent smart home devices and are used to control them. This increases playfulness and exploration. The robot also engages the user via socially expressive gestures. (b) *Unobtrusive*—the robot avoids interruptions unless there is a critical matter. It uses peripheral gestures instead of traditional notifications, and alerts about unexpected occurrences through subtle changes in its idling movement. (c) *Device-like*—the robot is designed as a microscope-like desktop device, which the user operates. It does not have an anthropomorphic face, but an expressive monocular rotating dot for facial expression. (d) *Respectful*—inspired by a butler metaphor, the robot rises to the user's attention when they are within the robots range, and goes back to a neutral pose when the user walks away. To provide more information, the robot exposes a hidden screen with a low bowing gesture. (e) *Reassuring*—form factor and size were selected based on user studies to convey reassurance and reliability. The robot provides feedback about home device status by examining the phicons placed on its turntable. It uses short acknowledgment gestures and sounds when parsing voice commands.

Our work also presents novel HRI design elements that have not been previously explored. These include the combination of human-robot interaction with tangible interface objects; the use of physical icons as both representing the information in smart home devices and for their control; a hidden screen that is revealed only when necessary through an expressive gesture; the transition of the robot from being a passive device-like tool to having social agent characteristics; and the design of a 1-DoF rotating dot for facial expressions.

Along our design process, we conducted exploratory user-centered design studies to examine our design decisions, in the spirit of paper prototyping [32]. These were run with a small sample from our target user population. The next step is to conduct a larger-scale evaluation of the final prototype along the stated design goals. We are also in the process of using Vyo to evaluate other aspects of domestic interaction. We hope to further understand interaction patterns with a device-like home robot that communicates with the users and the home via tangible objects.

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