"Haru": Hardware Design of an Experimental Tabletop Robot Assistant

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ABSTRACT

This paper discusses the design and development of an experimental tabletop robot called "Haru" based on Design Thinking methodology. Right from the very beginning of the design process, we have brought an interdisciplinary team that includes animators, performers and sketch artists to help create the first iteration of a distinctive anthropomorphic robot design based on a concept that leverages form factor with functionality. Its unassuming physical affordance is intended to keep human expectation grounded while its actual interactive potential stokes human interest. The meticulous combination of both subtle and pronounced mechanical movements together with its stunning visual displays, highlight its affective affordance. As a result, we have developed the first iteration of our tabletop robot rich in affective potential for use in different research fields involving long-term human-robot interaction.

KEYWORDS

robot design, design process, robot assistant, holistic design, tabletop robot, holistic design

ACM Reference Format:
Randy Gomez, Deborah Szapiro, Kerl Galindo, and Keisuke Nakamura. 2018. "Haru": Hardware Design of an Experimental Tabletop Robot Assistant. In *HRI '18: 2018 ACM/IEEE International Conference on Human-Robot Interaction, March 5–8, 2018, Chicago, IL, USA.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3171221.3171288

Figure 1: tabletop robot hardware Haru

1 INTRODUCTION

Advances in AI technology have ignited interest in intelligent systems in the household. This trend is evidenced in the adoption of smart devices equipped with virtual assistants such as Apple Home Pod, Amazon Echo and Google Home. Human beings seem to be fascinated by the experience of interacting with these smart devices, regardless of their very simplistic task completion and the absence or limitations of their visual affordance. The success of these smart devices has yet to be replicated in the realm of robot assistants. Unlike these smart devices, in which the interaction experience is predominantly focused on the voice modality, robot assistants can take advantage of the design elements afforded by their form factor, shape, size and movements. These elements when combined with vocalization, through synthesized speech and sounds have the potential to lead to a more visually engaging, immersive and interactive experience.

Although a robot's physical attributes can be an inherent advantage over those of virtual assistants, if left unchecked these could also be an Achilles heel. Various studies confirm that human expectations are shaped by the physical attributes of a robot [1][2]. As a consequence, human expectations can set the bar high depending on the promise it holds as a function of its physical appearance and how this measures up with the robot's actual affordances. For example, a six-foot-tall humanoid robot with a futuristic look would turn out be a disappointment if it only performed Q&A tasks and nothing more. This indifference does not impact on the smaller and basic-shaped smart devices, as the simple Q&A task completion of current smart devices is proportional to the simple image they project. The physical and aesthetic elements of a robot require considered design as they affect its prospect of acceptance and long-term adoption. It is essential to foresee in advance the implicit illusionary functionality brought upon by the design of the robot's physical affordance, and to strike a balance between

HRI '18, March 5–8, 2018, Chicago, IL, USA

ACM ISBN 978-1-4503-4953-6/18/03…$15.00
https://doi.org/10.1145/3171221.3171288

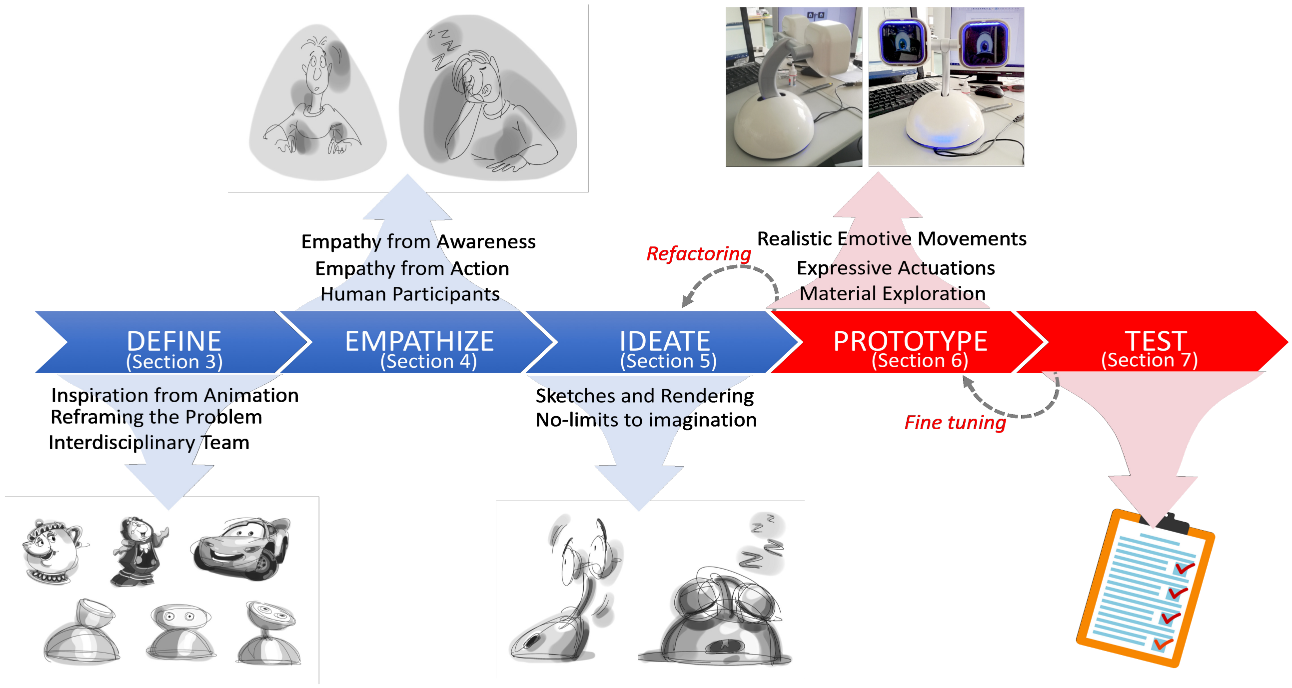

Figure 2: Schematic diagram of the design methodology.

this and human expectation. Keeping human expectation low while stoking interest at the same time may prove to be a good strategy.

In this paper, we will report on the design and development of a small and unassuming tabletop robot assistant called "Haru" which means Spring in Japanese. We employed design thinking methodology in developing the first prototype referred to as Haru beta. We envision our robot assistant Haru as an experimental research platform for long-term human-robot interaction research studies . This paper focuses on the design and development process undertaken in resolving the surface appearance and physical affordance of Haru, our first tabletop robot. This process spanned approximately a year. In particular, it looks at the informed choice of methodology and team required to achieve a balance between human expectation, surface appearance, physical affordance and robot functionality. It aims for a fresh perspective in understanding the importance of assembling interdisciplinary teams that include professionals from outside the field of robotics from the early stages of the design process, in order to realize the potential of the minimum requirements of movement and physical form required for optimal emotional affordance. In-depth analysis of the use of specific elements for emotional expression will be discussed in separate studies and are not covered in the scope of this paper. Section 2, gives an overview of different robot hardware platforms with small form factors and of our design methodology based on a "design thinking" model [26]. In Sections 3-7 we discuss the different stages of the design process during the development of Haru. We conclude the paper in Section 8.

2 BACKGROUND

2.1 Social Robots Review

The research and development of robot hardware research platforms has been actively pursued in the last few decades, as indicated by the following notable examples. Kismet, a robot platform resembling a humanoid head and capable of generating facial expressions, was prototyped for social referencing by Cynthia Breazeal at MIT in the 90's [3][4]. The team later developed Leonardo, a full-bodied, animatronic, character robot with a life-like animal appearance for research into social robotics [5][6]. During this period, a robot called PaPeRo [7] was developed by NEC for the consumer market. A popular small form factor entertainment robot dog Aibo equipped with AI capabilities developed by Sony *Aibo* started selling commercially in 1999. Other humanoid robots with small form factors such as the iCub [9] and the much smaller-sized robot Nao [10] have also gained a considerable following in the robotics community. In 2017, the creator of Kismet and Leonardo [3][4] launched a commercial model called Jibo [11], touted as an advanced family robot, Jibo is a personal assistant robot that has a simple articulated head and body shape. Another tabletop robot specialized for multi-party dialog interaction is the back-projected, humanoid robot head Furhat [12]. Lastly, is the LG personal assistant robot unveiled in 2016 called the Hub, this robot has a circular, flat 'face' mounted into a curved conical body and allows integration with other virtual agents such as Alexa [13].

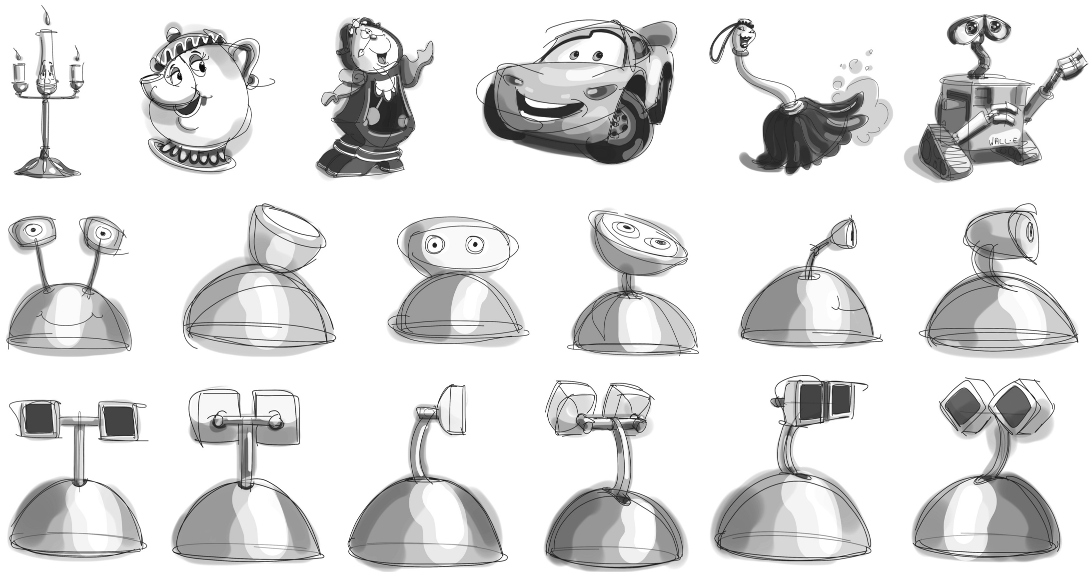

Figure 3: Top: Artists' sketches of animation characters from Pixar Animated Studios and Walt Disney Pictures; Middle: Artists' representative sketches of the different tabletop robot candidates during brainstorming; Bottom: Artists' sketches of the actual tabletop robot (Haru) after the deliberation process

2.2 Design Thinking

In designing Haru's physical appearance we aimed to step away from a literal humanoid or animal form, with its accompanying expectations, by experimenting with various form factors and shapes. Haru is an experimental tabletop robot designed as a research platform to test the limitations and potentials of a range of communication modalities within a framework of intentionally designed physical constraints. These constraints aim to strike a balance between keeping human expectations grounded while stoking human interest and supporting long-term interaction between personal robots and their users. To achieve our goals we assembled an interdisciplinary team which included professional outside of robotics and chose to employ a Design Thinking methodology from the beginning of our project. Design Thinking moves from the general to the particular through a circular process of reflective thinking, productive action, responsible follow through, and a constant reframing of the design problem. Each cycle of the design thinking model builds on understanding gained from the previous cycle, thus design thinking is also a process of constant iteration. This method has some fundamental commonalities with other methods, however, its advantage is that it is both an analytic and creative, human-centered process that requires an open mind to challenge limitations and assumptions, and provides a structure to experiment, create and prototype models for further feedback and redesign [17]. The process involved a continuous flow of ideas/brainstorming, moments of stepping away from practicalities, interdisciplinary teamwork, input from users and an iterative design cycle. The Design Thinking model reflecting a five-step process is depicted in Fig. 2 [18]. This was applied to Haru's ongoing design and development process. In the following sections we detail aspects of the application of a design thinking approach with specific reference to Haru.

3 DEFINE

The first step in the design thinking cycle is to define the problem. At this stage adherence to the human rule becomes an important issue as all design activity is ultimately social in nature [19]. The understanding that every product delivers a service and that humans use this service means that the design of personal robots must satisfy human needs first. This underlies the importance of solving both technical and social problems in ways that relate to human needs, rather than just for technical or economic efficiency. As a result, we must define the problem in a human-centric fashion. By defining the problem in this manner, research and further iterations on the domestic robot will be focused on a goal-driven perspective of the human being. In the case of Haru, the initial problem is, how can we meet the aim of designing an emotive, anthropomorphic tabletop robot for long-term human interaction within the limitations of our designed constraints, and with an open mind, who do we need to work with to do this. Later in Section 4, we will discuss how human volunteers were involved in the process of designing Haru's emotive affordances.

3.1 Inspiration from Animation Characters

It is not only technological advances that have created a market for social robots. Animated movies have played a large role in developing acceptance of wide spread human robot interaction in the future. The expertise that designers and animators bring in creating the 'illusion of life' in inanimate objects is key in developing a personal robot that interacts more as a companion than a personal

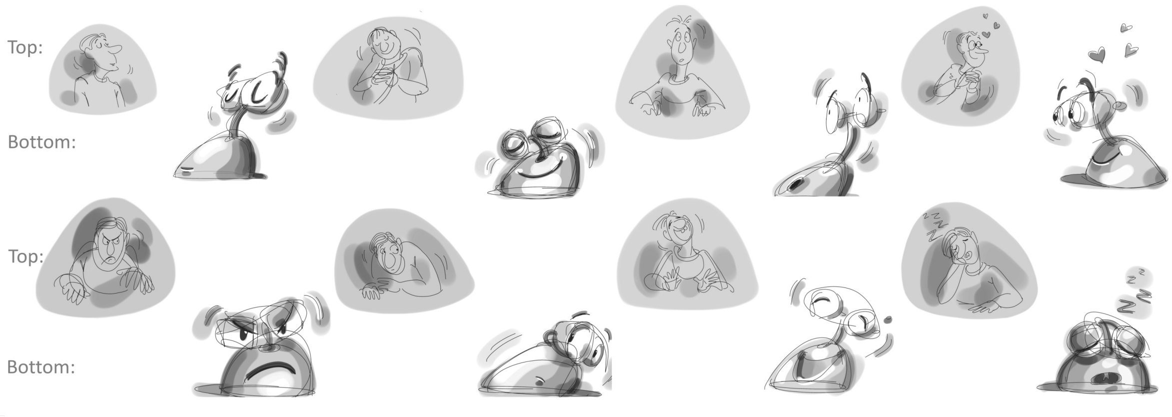

Figure 4: Top: Acted-out emotive actions from performers; Bottom: Artists' rendition of robot emotion synthesized from performers' acted out emotive actions.

assistant or talking computer. This correlation between animation and robotics has been recognized as a tool in aspects of robotic design such as the development of personality [14], in Hoffman and Ju's prioritising of movement over aesthetic form [15] and as a strategy to enhance emotional expression once a robot has been designed [16], in general, animation expertise has been utilised at late stages of the design process. In designing Haru, we chose to work with animators from the beginning of the design process. As we are looking at our approach to the research and design process in this paper, we will give an overview rather than specifics of the design and animation contribution to this research project to date.

An aspect of animation and design that is a core skillset can assist in 'giving life' to a robot's personality and can have a positive influence in how humans perceive robots. Fig. 3 (Top) illustrates the early design process where we researched popular anthropomorphized animated characters in order to analyze features and expressive possibilities to incorporate into our robot's design. From these animated characters the team started to sketch different kinds of tabletop robot candidates in Fig. 3 (Middle). We investigated and scrutinized each of the elements and after several brainstorming and deliberations we arrived at the early sketches of Haru as depicted in Fig. 3 (Bottom).

3.2 (Re)framing the problem

The first Design Thinking step taken is to (re)frame the problematic approach to constraints by framing them as opportunities. Although Haru is constrained in size, detailed features, horizontal movement and degrees of Freedom (DOFs), its design still provides opportunities for developing expressive and responsive communication modalities and the illusion of autonomy and agency necessary to satisfy human interest and interaction.

In particular, Haru's design incorporates, two eyes with LCD screens, LED rim and movement capability, an LED matrix mouth plus the ability to work with a range of movements, voice and sound effects (Haru's hardware is explored in detail in Section 6). Each of these elements provides fertile research ground for developing an expressive and emotive multi-modal communication system between Haru and its user. This lead to a new definition of the problem space, which is, what is the best approach to realize the potential of Haru's communication modalities. Specific factors within Haru's design, such as the small form factor, height and shape were initially arbitrary and based on people's (i.e. design team) preferences. These were later refined and tested with the hardware, to leverage form factor with functionality as discussed in Section 7. This process resulted in a design that incorporated aesthetics and personality with a meticulous combination of both subtle and pronounced mechanical movements, stunning visual displays and sound to achieve affective affordance. These elements are key factors that we will be exploring with designers and animators in our new definition of the problem space of how to realize Haru's potential.

3.3 An Interdisciplinary Team

Reframing a problem revolves around a deep understanding of human needs and the needs to reflect on themes outside the context of the original problem, in order to develop new perspectives [20]. Moreover, there is a need to work with a network of 'interpreters' in order to study how people create meaning [21]. This highlighted the importance of assembling an interdisciplinary team from the beginning of the design process, one that encompassed technical, design and social problem solving skills in order to realize Haru's potential. In this light we embraced the expertise of designers, animators and sketch artists in our interdisciplinary team. Their specific role is to bring their professional skills as human-centered problem solvers and as 'interpreters' who design narrative and meaning within aesthetic, technical and social parameters. It is their particular task to work with our hardware and software designers to realize the potential of Haru's communication modalities.

4 EMPHATIZE

The Design Thinking process begins by seeking empathy and insight into the situation of those who are being designed for. This requires being able to put yourself in the place of another person and understand what they are thinking and feeling. Given that our aim is to design a personal robot that people interact with and performs the role of companion, empathy is a key consideration. Empathy makes human behavior unique and has been identified as the main downfall when it comes to maintaining the illusion of life in robotic behavior [22].

4.1 Participants

We asked 50 volunteers referred to as "performers" ranging from age 20-55 years old in which both genres are equally represented. We explained to them the nature of the experiment and showed them the initial sketches of the robot. We also utilized 3 professional sketch artists and 9 of the team members grouped into 3 clusters to act as observers or "coachers". Each cluster has one sketch artist allocated.

4.2 Empathy Through Action

Body language, such as the way we express our tone, our gestures, our proximity with other people and how we present ourselves are all based around the idea of expressing emotions [23]. The performers were asked to act out emotions through certain combinations of body language expressions. Emphasis was given to the manifestation of emotion in the face; the movement of any parts of their body; how a person holds their arms (whether the weight is held low in the shoulders or up high), the position of their head or neck (a head held high or held low), the posture of the spine (high or low), the position of their hips (high and low), the weight of their movements (light or heavy) as depicted in the sketch in Fig. 4 (Top). The volunteers were asked to join each of the three clusters and perform two sets of emotive actions. Specifically they acted out emotions as themselves and were then asked to act out emotions assuming that they were Haru. This particular study allowed us to collect several variations of emotions being acted out.

4.3 Empathy Through Awareness

To capture the variation in intensity and subtleness of different emotive action and performance, we set up a camera and a display in which the performers then made fully aware of their expressions. They were being observed and instructed by the "coachers" to express their body language or facial expression with varying intensity (e.g. less happy, moderately happy, extremely happy, etc.). The video display served as a feedback to the performers in which they could effectively modulate the intensity and subtlety of the acted emotions. As the performers act out these coached actions, our sketch artists take notice.

4.4 Synthesising Haru's Affordance

At this stage, we categorized movements and expressiveness into a distribution of activity percentages in three major parts of the human body. The results are set out in table 1. Note, the lower body is used less in expressing emotion (6%) pointing to physical attributes we could eliminate (i.e. lower body and legs) while still retaining

Table 1: Percent distribution of communicative expressiveness (area of body)

Upper Body (head, neck, face and eyes)	44.0 %
Middle Body (arms and body)	50.0 %
Lower Body (legs and feet)	6.0 %

Table 2: Percent distribution of movement prominence

Lean backward/forward	18.0 %
Nodding/Tilting of head etc.	13.0 %
Swaying of head Left-to-right	11.0 %
Swaying of the whole body	19.0 %
Arm-and-hand movements	26.0 %
Eye movements	9.0 %
Feet Movements	4.0 %

emotive affordance. This persuaded us to focus the design on head, neck and middle body. In simplifying Haru's embodiment, Haru's design can be perceived as a whole face with elements of the face also allowing the perception of an upper and middle body. Analysis indicated 26% of emotional communication related to the hands and arms. Arms also have the added advantage of directing gaze location. However, the addition of arms would not only complicate Haru's design, it would add to user expectations as arms are also associated with physical task capabilities. We resolved this issue by reviewing our prominent movements findings in table 2. These findings led us to eschew the unibody design common to many contemporary robot designs. We realised that by separating Haru's eyes and allowing them a forward and backward tilt as well as the ability to pivot and indicate direction, they could serve the same communicative purpose as the notion of 'arm' and 'hands', thus enabling more effective communicative affordance. Results below evidence prominent movements of body parts observed during acting-out, helping determine DOFs and moving elements or parts of Haru that can potentially invoke emotion.

5 IDEATE

This is a brainstorming process that we are used to, however at this stage in the design thinking process, the ambiguity rule, defined by the need to maintain an open mind by allowing for chance discovery [19], must be adhered to in order to successfully generate as many ideas or problem solutions as possible. Limitations such as the solution's impracticality must be overlooked in order to facilitate a continuous flow of ideas and stimulate free thinking in order to expand the problem space [24]. These ideas were then tested in the prototype stage, which we will talk about in Section 6, to solve or perceive the originally defined problem in an alternative perspective.

In this stage, the team brought to life Haru through sketches and rendering based on the acted out emotive actions discussed in the previous section. Haru's mobility and display components were now beginning to take form. Primarily, there is no limitation in this stage as to what Haru should look like and what Haru can do. The only guiding principle is for Haru to convey a visually

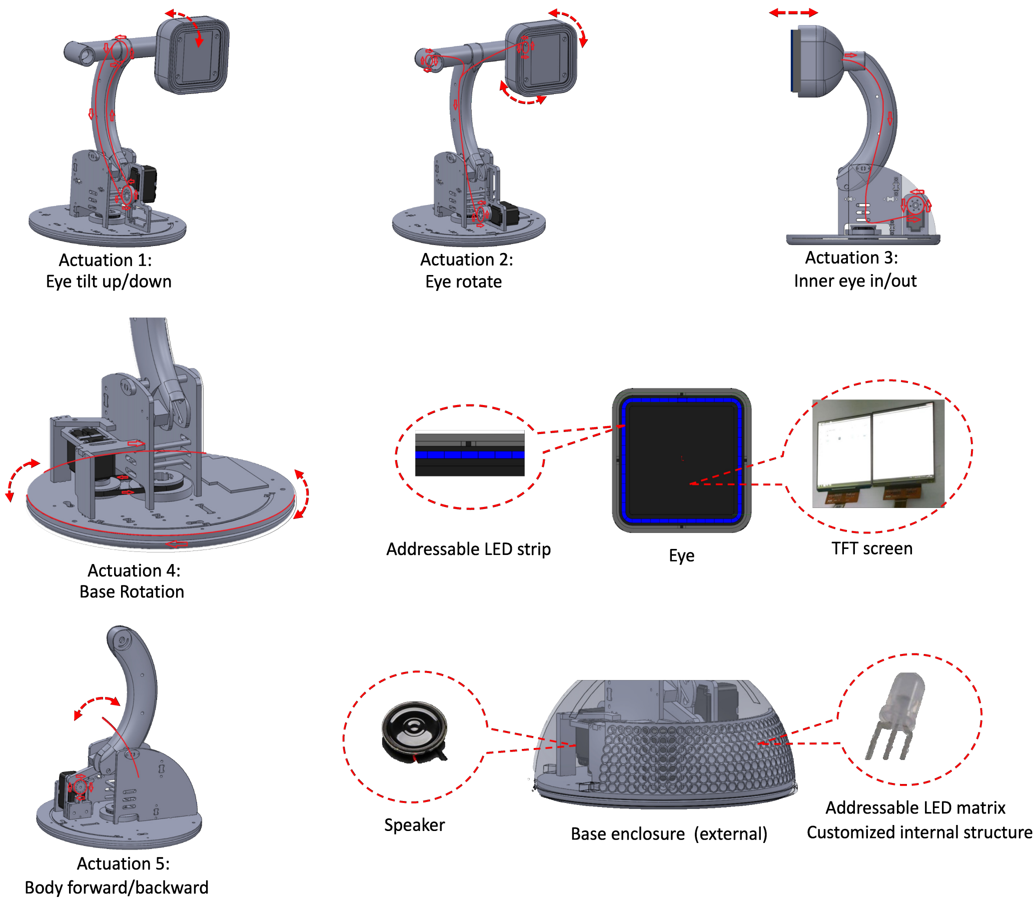

Figure 5: Haru's materials and components.

engaging emotion using the acted out emotion in Fig 4. (Top). The interpretation of what is 'visually engaging' lies primarily to the designers' creative and artistic interpretation void of constraints from the engineering requirements. The team continues on the brainstorming process with the help of the sketch artists. Samples of the sketch artists' rendition are illustrated in Fig. 4 (Bottom).

6 PROTOTYPE

In keeping with a design thinking model, it was important that any prototype of Haru embodied the hypotheses and ideas developed during our ideation stage. It is important to treat this as an experimental stage that tests the theoretical assumptions and moves the project forward by facilitating further research and discussion informed by the practical and tangible properties of the working prototypes [19]. The importance of 'rapid prototyping' and iteration as a way to address the dilemma of the day to day needs of real world practice, design issues and practical issues that would otherwise not be recognizable in theoretical research are highlighted in [25]. During the prototyping stage we examined and studied various kinds of form factors and shapes and sizes for the tabletop robot. In revisiting the previous processes in Fig. 2, we had to refactor some of the design concepts that were difficult to realize in the engineering domain. The finished hardware is shown in Fig. 1.

6.1 Material Exploration

The robot's build is shown in Fig. 5. The base of the robot has a diameter of 220 mm which is the minimum size to fit all of the actuators needed for movements, addressable LED matrix display, micro speaker and the electronics control board, respectively. For a uniform dispersion of light, the LED matrix display is housed in a customized structure that snugly fits the curvature of the external body casing. In Fig. 1, the LED matrix display is activated to project a smiling mouth from the inside. The electronic control board is the central processing unit of the robot that is responsible for all motor actuations, display signaling, vocalization through the speaker, etc. It has both wireless (e.g. bluetooth and wifi) and wired connection via usb to communicate with the outside world.

The body of the robot, resembling a hollow curved tube, is 143 mm in length. The body serves as the pathway of all the strings that are connected to the actuators in the base, controlling the eye movements. The eye itself is composed of an outer shell which

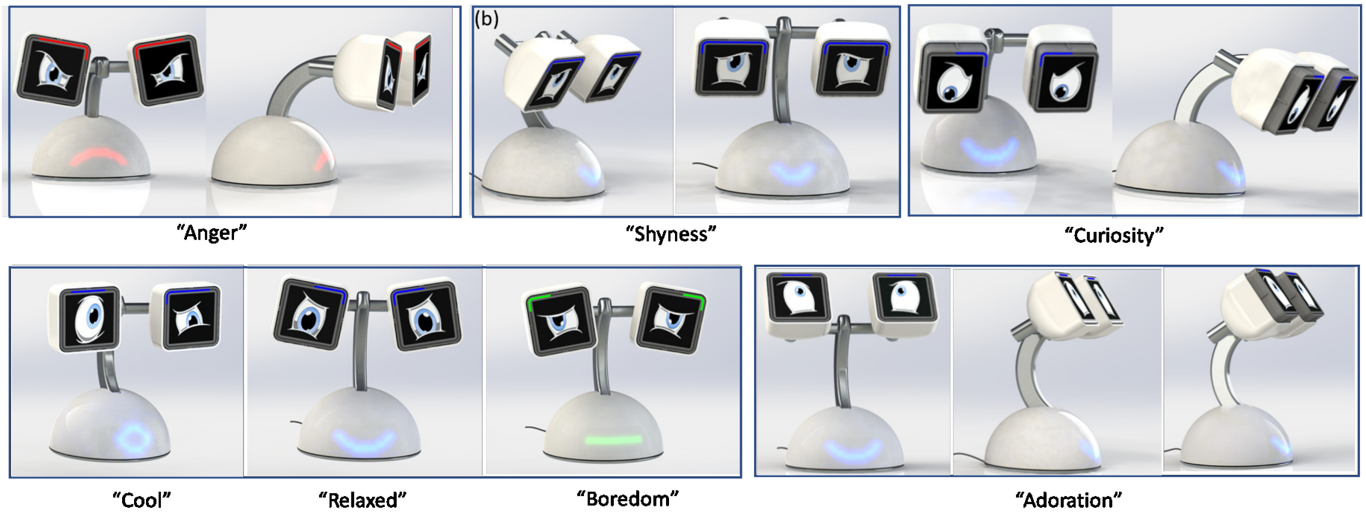

Figure 6: Haru's actual hardware emotive affordance.

is 95.5 mm x 95.5 mm x 61.19 mm in dimension, and the inner eye contains the a 3-inch TFT display to render the affordance of the robot's eye. The display has a built-in graphics rendering system with an on-board storage device. Animated eye movements can be stored directly to the TFT's internal storage and can be controlled wirelessly from the electronics control unit in the base. This mechanism reduces the number of wires running from the base through the body and the eyes. The border of the eye is embedded with an addressable LED strip to reinforce the visual affordance of the eyes through light and color effects. The left and right eyes are separated via a "T" frame perpendicular to the neck. This allows communication of direction in the same manner of a hand, however, in keeping with our goal, it keeps human expectation of Haru in check.

6.2 Expressive Actuations

Haru's 5 degrees of freedom as depicted in Fig. 5 (Top) are described as follows:

Actuation 1: Eyes Tilt Up-Down
Tilting of both eyes at the same time in an upward or downward direction for a total of 60 degrees angle displacement. This actuation refines eye contact posture of the robot with the user and at the same time expresses intent of adoration, shyness, etc.

Actuation 2: Eyes Rotation
Rotation of both eyes towards the inner and outer part of the body from [-45,45] degrees angle. This actuation may be used to express various kind of intentions such as curiousity, doubtfulness, etc.

Actuation 3: Inner Eyes In-Out
Simultaneous retraction and detraction of the inner eyes with a total of 15 mm displacement. This particular actuation of the inner eyes communicates surprise and fear, among others. These actuation can further refine the intensity of "advance", "retreat" and "curiosity" when combined with Actuation 5.

Actuation 4: Base Rotation
Panning of the base with a total displacement of 320 deg angle. The base of the robot is composed of a solid steel frame in which it pivots. The internal custom-made LED matrix that constitutes the mouth of the robot rotates together with the base. The base actuation is used to track human's azimuthal movement and may be used to convey other social signals such as "disagreement" when it is allowed to oscillate in a clockwise and counter clockwise direction, among others.

Actuation 5: Body Forward-Backward
Forward and backward movement of the body allows for a total displacement of 57 deg angle. The forward mechanism may convey a social signal of aggressiveness, interest, and curiosity, while the backward movement mechanism may express "retreat", "fear", etc.

6.3 Realistic Emotive Movements

After factoring all of the physical limitations and practicability issues in terms of hardware, we are able to generate the possible bodily movement and visual displays of Haru as depicted in Fig. 6. These are just one of the few examples of the social signals of Haru. The promise of a much richer emotive affordance is achievable when combining movements and vocalization as well, which will be pursued in a separate and independent study.

7 TEST

In this testing stage of the process, we enlisted our original volunteers and evaluated a limited range of Haru's visual emotive affordances. We then used our findings to make refinements to the current prototype of the robot hardware. This stage was not intended for a grand user interaction study, instead, it was primarily focused on improving the prototype. User studies on the

Table 3: Participants' preference of Haru's size

40% of actual size	17.0% approved
60% of actual size	24.0% approved
100% of actual size	47.0% approved
130% of actual size	10.0% approved
160% of actual size	2.0% approved

effectiveness of Haru will be conducted and discussed in a separate work.

7.1 Visual Emotion Affordance

One of Haru's future competencies is to be able to identify human facial affects. Moreover, Haru has to be able to express emotions through bodily movements and visual elements, such as eyes, sound, color, mouth, etc. We conducted a wizard-of-oz experiment in which we ask the same 50 participants in Section 4 to participate in the test. The participants were made to believe that Haru could recognize emotions through bodily movements and facial effects. In this experiment, we tested a limited range of three critical universal emotions: happy, sad and angry, and programmed Haru to perform routines to express them. We reserved complex emotions for a separate study. The participants were then asked to show bodily movements or facial effects for each of the three emotions and the "wizard" executed the corresponding routine. The participants were then asked two questions. Firstly, if Haru correctly mirrored the emotion that they had acted out and secondly, whether Haru's performance satisfactorily communicated the emotion. The results of this simple experiment were that 95% of the participants confirmed that Haru correctly mirrored the emotion they had acted out and, approximately 80% were satisfied with Haru's communication of the emotion.

7.2 Different Sizes

The size of Haru was a difficult decision which took nearly 20% of the allocated design time frame. Different models of Haru with varying dimensions were produced and then narrowed down into five sizes namely, 40%, 60%, 100%, 130% and 160%, respectively. We note that 100% refers to the size of the current prototype of Haru (Sec 6.1). This experiment was the most compelling reason of the choice of Haru's size. This was backed up in a poll of team members in respect for Haru's optimal size. Almost half the team members had a preference for the current size, as outlined in the table 3.

8 CONCLUSION

We have showed the design and development of the first tabletop robot iteration, Haru beta. In this paper we have chosen to focus on the development of Haru's visual elements along with our decision to work with a design thinking model and an interdisciplinary team which includes professionals outside the field of robotics from the beginning of the project. These elements reflect essential elements of our research and development process however, they are only some of the aspects that we have addressed in our design of Haru. We will discuss other issues in the development of Haru's design and its expressive and responsive communication modalities and interaction in the future.

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