SquishiSense: Exploring how giant, interactive, inflatable robots can affect users' moods

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1 ABSTRACT

SquishiSense is a novel, giant, inflatable robot that is emotionally responsive to human interaction. The unique characteristics of a large robot offer prospects for human-robot interaction that are not viable with smaller robots; in particular, users can climb, be embraced by, or squished by the robot. There tend to be small, rigid, interactive robots primarily used as companions (3.1) and large, soft, non-interactive robots used as art installations (3.2). However, there is a notable absence of a robot with combined features of the two: interactive, large and soft, which provide full body immersive interactions. Our main aim is to construct a large, soft, inflatable robot that can sense human touch through the use of ultrasonic sensors and provide sensory feedback, such as colour and sound, giving the users an increased sense of control and a more engaging experience. It has potential applications in enclosed public spaces, such as art galleries or shopping centres, where people may require a designated area to decompress and regain focus amidst overwhelming environments. Our robot's size and shape significantly influence the user's experience, particularly in terms of providing full-body interaction and creating a comforting, engaging, and pleasing environment conducive to various modes of interaction. Through our studies (for study 1, n=53 [4]; for study 2, n=15 [6]), we have found that SquishiSense can decrease heart-rates by 11.5 BPM post 5-minutes of interaction and improve users' moods by 2.2 points on a 10-point Likert scale.

Fig. 1. SquishiSense

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2 INTRODUCTION

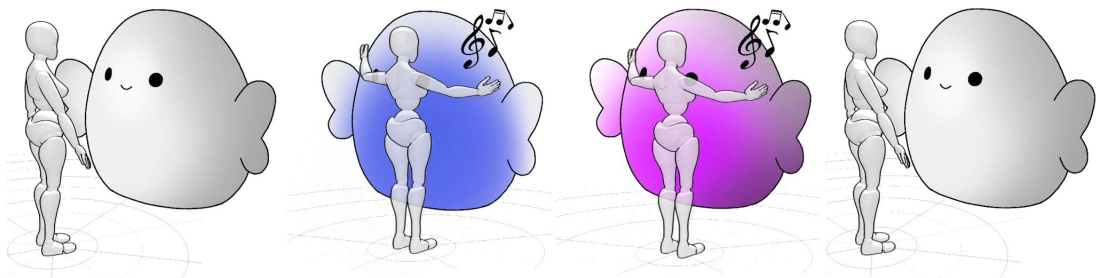

Fig. 2. Hugging SquishiSense results in colour-changes and calming music being played

The appeal of interactive robots in sectors including entertainment [20] , education [16], healthcare [14], and therapy [21] stems from their ability to offer immersive user experiences. However, a research gap exists for large, soft, robots capable of delivering personal human-robot interactions in enclosed public spaces, such as art galleries or shopping centres. In the domain of interactive robots, existing large inflatable robots present opportunities for further development in sensing and responding to human touch. By incorporating this functionality, it is possible to foster more emotionally satisfying experiences for users, providing them with a greater sense of control and autonomy. The field has predominantly focused on developing interactive robots for medical applications [18] and therapy treatments [12] with HCI yet to explore large-scale soft, responsive robots designed specifically for recreational and general well being purposes. Further, the large-scale soft robots employed in the entertainment and arts sectors currently lack mechanisms for detecting and responding to human touch [1].

By integrating innovative methods for sensing human touch and delivering sensory responses, our approach augments the capabilities of existing large, soft robots. In response, we present SquishiSense: a large-scale soft robot that combines the softness and pliability of large inflatable devices with real-time touch sensing and sensory feedback. SquishiSense employs ultrasonic sensors embedded within its PVC fabric to detect human interaction in real-time, providing immediate sensory feedback such as colour changes and soothing sounds for a relaxing and autonomous experience. This versatile full-body experience, where users can climb on, be embraced by, or even squished by the robot, establishes emotionally satisfying interactions surpassing traditional interactive robotic devices. Our empirical studies demonstrate the efficacy of this approach in enhancing user moods and promoting relaxation.

We believe our work extends the boundary of traditional interactive devices by opening up the user experience to full-body, touch-responsive human-robot encounters. To explore this, we conducted two studies: (1) a questionnaire to determine user preferences for shapes, sizes, and environments in which they felt comfortable interacting with soft inflatables, with respondents indicating a preference for small private rooms, such as those found in art exhibitions or busy enclosed areas like shopping centres (see 4); and (2) a user study exploring how users interact with the robot in a busy room, assessing whether the interaction was interesting and whether participants felt more relaxed after the interaction (see6). We found that SquishiSense can decrease heart-rates by 11.5 BPM post 5-minutes of interaction and improve users' moods by 2.2 points on a 10-point Likert scale.

We believe that SquishiSense can be applied in places such as art galleries or shopping centres. Based on our Study 2, where we conducted a user evaluation in a busy room, we believe SquishiSense has the potential to deliver engaging, interactive experiences while also providing individuals with an opportunity to decompress and regain focus amidst overwhelming environments (see 6). In contexts like art galleries, traditional exhibitions have restricted meaningful engagement through their "look but don't touch" approach to art appreciation. SquishiSense's real-time touch-sensing capability opens up the possibility for interactive exhibitions, enabling visitors to engage with art tactually. Moreover, in the context of the COVID-19 pandemic, SquishiSense offers an additional benefit of providing a hygienic means for physical interaction, with its easy-to-clean PVC cloth material. This promotes tactile and skin-on interactions while mitigating transmission risks.

In this paper, we first introduce SquishiSense's design, derived from interaction design principles and initial user study data (see 4). Subsequently, we explore SquishiSense's novel construction, which facilitates less restricted user interactions through the use of ultrasonic sensors embedded beneath the PVC material. Finally, we highlight how the further development of emotionally responsive, large-scale soft robots present open research opportunities with potential applications that could have a significant impact on society.

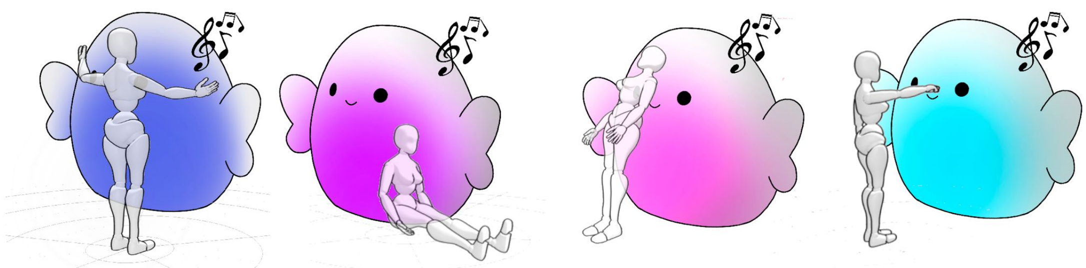

Fig. 3. Different modes of interaction with SquishiSense

3 RELATED WORK

Over the past few decades[11][5], the field of robotics has experienced an influx of innovative research and development. These robots span a wide range of capabilities, from simple toys[10] to advanced robots with sophisticated features [24]. Early research in the 1990s and 2000s focused on robots for the application of "benign" social behaviour, with interactive robots typically designed as companions, assistants and pets[11]. While recent studies, such as Cynthia Breazeal's 2017 publication[5], discuss the evolution of these robots and their transition from research to commercialisation, showcasing the shift towards understanding and addressing the complexities of human-robot interaction. Despite these efforts, there remains a scarcity of robots that seamlessly blend the attributes of being inflatable, interactive, and large. This paper delves into the current state of the literature, exploring various robot types, their applications, and how they have evolved over time while identifying gaps and opportunities for future research.

3.1 Interactive / Soft Robots

Interactive robots are types of robots designed to engage in dynamic, social, and physical interactions with humans. Typically leveraging artificial intelligence, computer vision, and sensor technologies, these robots can perceive and interpret human emotions, expressions, and gestures[8]

One notable example is Pepita[17], a small, huggable, social robot capable of sensing and conveying affective expressions through tangible gesture recognition and projected avatars. Designed as a companion robot, Pepita senses two types of tactile gestures: hugs as a positive message and pulling the tail as a negative message. The system translates these actions into visual feedback by projected avatars, designed to convey a positive affective expression, such as happy, and a negative affective expression, such as sad. The decision to use projected avatars as the medium for conveying affective feedback was based on the results of a questionnaire conducted by the researchers. Participants were asked to evaluate the effectiveness of both projected avatars and coloured lights in communicating positive and negative affective expressions, with results indicating that projected avatars were slightly more effective.

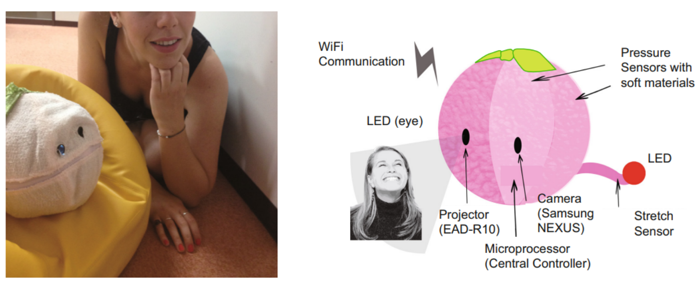

Fig. 4. PEPITA: System overview of the developed robot pet [17]

Furthermore, another robot is Paro, the Therapeutic Robot[13], an advanced interactive robot specifically developed to offer emotional support for elderly individuals with dementia or other cognitive impairments.This innovative robot brings the benefits of animal therapy[3] to environments such as hospitals and extended care facilities, where the presence of live animals presents logistical challenges. Designed to resemble an endearing baby harp seal, Paro is equipped with an array of sensors that enable it to detect and respond to touch, thereby contributing to its lifelike behaviour. The sensors include tactile, light, auditory, temperature, and posture sensors, enabling Paro to perceive people and their surroundings effectively. The tactile sensor enables Paro to differentiate between being stroked and other forms of touch, while the posture sensor assists in detecting when Paro is being held. In response, Paro behaves as if it is alive, moving its head and legs while making sounds. Research has demonstrated that interaction with Paro yields several benefits, including reducing negative emotions and behavioural symptoms, improving social engagement, and promoting positive mood and quality of care experiences [3].

The aforementioned examples, Pepita and Paro, exemplify the state of the literature on interactive robots, which predominantly focuses on small and rigid designs. However, such form factors may constrain the scope of potential applications and interactions. In contrast, the comparatively underexplored domain of large, interactive robots could potentially provide increased interaction opportunities and broaden use cases as a result of their sizable presence, warranting further research and development.

3.2 Inflatable Robots

Transitioning from purely interactive robots, another significant area of research within the field of robots is the development of inflatable robots. Such robots are characterised by small, interactive and large, non-interactive implementations, [9][19] [1]with large, interactive implementations not yet fully explored.

Puffy [9]serves as a prime example of a small, inflatable interactive robot specifically designed to provide social and emotional support for children with neurodevelopmental disorders. Inspired by Disney's Baymax from the movie "Big Hero 6," Puffy stands approximately 130 cm tall and features a soft, inflatable body responsive to touch. Puffy's design, which matches the height of the target children, incorporates arms, speech capabilities, and other human-like features to facilitate engagement and support during treatment. Further, Puffy utilises projectors to display a variety of games and images on its surface.

Fig. 5. Puffy: Puffy interacting with pre-schoolers [9]

A seminal body of research in the realm of large inflatable robots is the work of AirGiants [1], a UK-based company specializing in the design and production of large, pneumatically-controlled inflatable structures for events and entertainment. These structures, made from durable PVC material and ranging in height from 5m to over 30m, adopt various forms such as animals, buildings, and abstract shapes. While not interactive, the installations captivate audiences by providing memorable, hands-on experiences through physical engagement and emotional expression.

Fig. 6. AirGiants: One of the inflatables AirGiants have made [1]

Another notable development in inflatable robotics is a soft inflatable arm[19] for telepresence robots, designed to imitate human arms for remote interaction. This lightweight arm, weighing approximately 50 grams, is made from a common, low-cost, and environmentally-friendly inflatable material. It enables agile movement by pumping air at low pressure, allowing for safe and direct human contact without external sensors. Experimental results demonstrate that the soft inflatable arms can not only perform agile movements, but also execute more complex motions, such as dancing, thereby expanding the potential applications of inflatable robotics.

3.3 Touch in robotic interaction

The integration of the sense of touch in robotic interaction is said to facilitate a more seamless and meaningful connection with humans, addressing the constraints in interaction and cognitive capabilities faced by robots devoid of tactile feedback[7]. Consequently, researchers have been prompted to explore the integration of tactile sensations in robots, further driven by the emotional and health benefits associated with human touch. [6]

The Huggable [22]robot exemplifies such an approach, incorporating tactile sensations in human-robot interactions. It is equipped with temperature, force and electric field sensors strategically concealed beneath a layer of silicone and fur, enabling the robot to detect and respond to human touch during a hugging experience. Despite these advancements, it falls short of accurately replicating a human hug due to its small size and inability to measure and reciprocate the pressure exerted during a hug[23]. Consequently, ongoing research endeavours to create robots that offer a more human-like hug experience, simulating the softness, warmth and responsiveness characteristic of a genuine embrace[4].

In conclusion, existing literature on interactive robots primarily focuses on small, rigid designs, as illustrated by Pepita and Paro, while inflatable robots generally encompass small interactive or large non-interactive forms, as exemplified by Puffy and AirGiants' creations. Further, the significance of touch in augmenting human-robot interactions and cultivating meaningful connections has been demonstrated through the integration of tactile feedback in robots such as the Huggable. Notably, the literature reveals a gap in the exploration of large, interactive and inflatable robots. This paper addresses this lacuna by presenting a large, interactive inflatable robot that not only fills the identified gap, but also integrates the crucial element of tactile feedback to foster meaningful connections. Consequently, our work establishes a foundation for further research and development in this underexplored area, providing a comprehensive understanding of such robots' potential advantages and limitations.

4 STUDY 1: USER GATHERING DATA

Through a preliminary study, we aimed to gather feedback from participants concerning the design of SquishiSense. Our primary areas of focus included:

- Respondents' general attitudes toward soft, inflatable robots
- The shapes and sizes they would find most engaging
- The types of response from the robot they would find most pleasant
- The environmental setting they would feel most comfortable engaging with large, soft inflatable robots

Acquiring such data helped us gain an understanding of people's preferences and expectations of the robot, thereby enabling us to refine SquishiSense's design to facilitate mood-lifting experiences.

4.1 Participants

We recruited 53 participants, of which 27 were female, 23 were male, and 3 other. All respondents are aged 18+ and among the respondents, 50 had no prior experience interacting with soft, inflatable robots.

4.2 Questionnaire Design

An online questionnaire was chosen as the preferred data collection method due to its ability to garner a large, geographically diverse respondent pool, and yield valuable insights into user preference for SquishiSense's features. This approach is particularly important for our project, as it explores themes of hugging, physical interaction, and attitudes towards robots, which can be influenced by factors such as age, cultural background, and socioeconomic status. This method facilitated the acquisition of unbiased individual responses, reducing the likelihood of opinions converging and promoting more in-depth input from all participants, which may be challenging to achieve in group settings like focus groups. The questionnaire design was structured to address various aspects of user preferences and expectations, including:

4.2.1 General attitudes to soft, inflatable robots. Participants were asked to envision interacting with soft, inflatable robots and subsequently provide details concerning their preferred modes of interaction and the aspects of these robots they would consider inviting or interesting.

4.2.2 Shape preferences. Participants were questioned about their preferences for robot shape, such as a more or less human-like form, and were then presented with a series of shapes to rank based on engagement, intimidation, and comfort. As can be seen in image 1, we presented participants with a diverse array of shapes featuring animal-esque

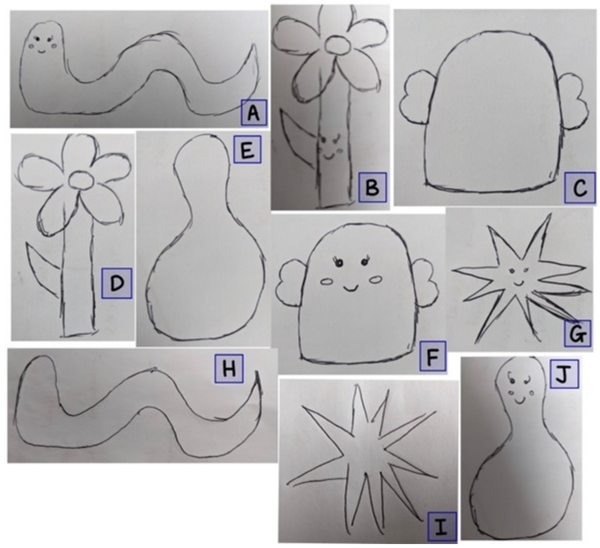

Fig. 7. Sketches of Potential Shapes for SquishiSense's Inflatable Body

structures, jagged edges and smooth contours. This variety was deliberately chosen to capture a range of design alternatives, enabling us to discern user inclinations and better comprehend the aspects influencing user engagement and comfort.

4.2.3 Size preferences and tactile feedback. Participants were asked about their preferred size for a soft, inflatable robot and the type of feedback they would find most comforting upon touching it.

4.2.4 Sensory attributes. Participants were prompted to rank various colours, scents, sounds and textures from most to least comforting in the context of SquishiSense having such attributes.

4.2.5 Environmental preferences. Using a 5-point Likert scale, ranging from "Not at all comfortable" to "Extremely Comfortable," participants rated how comfortable they would feel while interacting with a large inflatable robot in different settings.

4.3 Results

In this study, we analysed the preferences and attitudes of 53 respondents with respect to soft, inflatable robots, focusing on aspects such as shape, size, sensory attributes and environmental preferences. Before delving into a detailed analysis of the data collected with each section presented in the same order as the questionnaire, we provide a summary of the overall findings that will inform the design of SquishiSense.

The findings indicate a generally favourable perception of soft, inflatable robots among the respondents, with a preference for those that are less human-like, rounded in shape and are large in size. Sensory responses, especially colour changes and auditory feedback, were identified as desirable attributes. Moreover, the participants expressed a greater expected level of comfort when interacting with these robots in settings such as quiet, private rooms or busy public spaces.

4.3.1 General attitudes to soft, inflatable robots.

Interest in interacting with soft, inflatable robots. A total of 34% (18/53) of respondents expressed a high degree of interest ('Very Interested' or 'Extremely Interested') in interacting with a soft inflatable robot. Interestingly, this number increased to 51% (27/53) when the robot considered was equipped with sensory responses, such as the ability to change colours. This observation suggests that the incorporation of interactive elements may enhance the appeal of such robots.

Preferred features and interactions. When asked about aspects of soft, inflatable robots that participants would perceive as inviting or interesting, 38% (20/53) indicated a preference for "soft" or "fuzzy" materials, 21% (11/53) cited colour, and 6% (3/53) emphasised the presence of a face. Notably, Respondent 18 expressed interest in "a colour feature that responds to touches," while Respondent 21 favoured the idea of "musical output". Furthermore, three respondents found the concept of an animal or "creature" design appealing, illustrating the diverse preferences and interests in the group.

Upon prompting participants to specify their preferred methods of interaction with a soft inflatable robot, 49% (26/53) of participants indicated a desire to hug the robot. Other suggested interactions encompassed talking to it (19%; 10/53), observing it (8%; 4/53), leaning or laying on it (8%; 4/53), punching it (9%; 5/53), squishing it (9%; 5/53), and attempting to exert control over it (8%; 4/53). Respondent 47 expressed interest in observing the robot's movement or performance, akin to a sculpture, while Respondent 28 was intrigued by the prospect of watching it illuminate. Notably, 89% (47/53) of the responses involved some form of tactile engagement with the robot. Additionally, Respondent 51 remarked that soft inflatable robots hold the potential to enhance artistic performances, such as those in music, film, or art exhibitions.

4.3.2 Shape preferences. Option F emerged as the top choice among respondents regarding comfort, aesthetic appeal and engagement, ranking ninth for intimidation, thereby establishing it as the most favoured shape overall. Rounded shapes, such as options F, C and J, consistently outperformed spiky shapes, such as G and I, in the context of comfort. Furthermore, shapes featuring faces consistently ranked higher in terms of comfort than their faceless counterparts, highlighting the influence of design attributes on the perception of soft, inflatable robots.

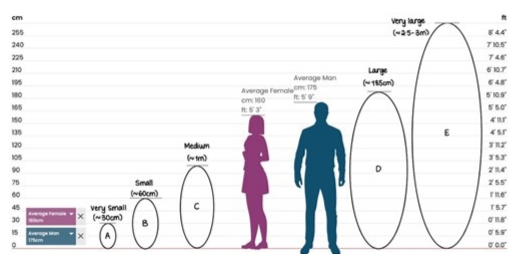

Fig. 8. Sizes provided in response to the question, "What size would you like a soft inflatable robot to be?"

4.3.3 Size preferences.

Importance of robot size. A substantial 77% (41/53) of respondents regarded the robot's size as at least "Moderately important" to their experience. In response to the question, "What size would you like a soft inflatable robot to be?", the median preference was "D. Large, approximately 185cm". Respondent 34, who answered "Large", elaborated on their choice, stating that "this means hugging-style interaction would be more inviting" and that they would find it "more comforting to be hugged by something bigger". Similarly, Respondent 5 noted that a larger robot would have a more significant visual impact. However, some participants expressed concerns about "E. Very large, 2.5-3m" as being excessively large. For instance, respondent 2 described it as "overwhelming", while Respondent 32 found it "scary", underscoring the need for striking a balance in size to cater to diverse user preferences.

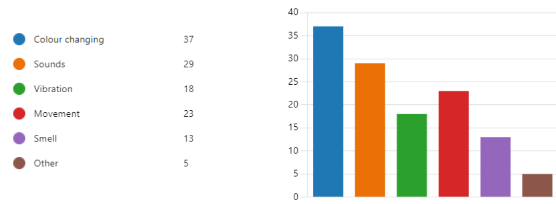

Fig. 9. Results from the question, "What feedback would be comforting/interesting from touching a responsive robot? (Select all that apply)"

4.3.4 *Sensory attributes.*

A majority of respondents (70%) indicated they would find "Colour changing" feedback comforting or interesting when interacting with a responsive robot. followed by sounds (55%). Conversely, the least popular sensory response was "Smell", with only 25% of respondents considering it comforting or interesting.

When asked to rank the sounds from most to least comforting, 'Ocean sounds' emerged as the top choice, with 40% of respondents ranking them as the most comforting, closely followed by 'Rainfall' (30%). In terms of colour preferences, 'Blue', followed by 'Purple' and 'Pink', were identified as the most comforting colours. For smells, 'Lavender' ranked the highest, followed by 'Freshly baked bread' and 'Mint'. Lastly, regarding textures, 'Silk' was perceived as the most comforting, followed by 'Cotton' and 'Velvet'.

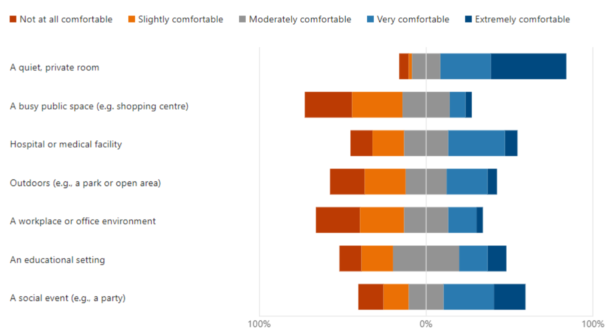

Fig. 10. Results for the question "In which of these settings would you feel most comfortable interacting with a large soft inflatable robot?"

4.3.5 *Environmental preferences.*

Importance of privacy. When participants were asked about the importance of privacy in settings where they would interact with soft robots, their responses varied significantly: 23% (12/53) considered it 'Not at all important', 13% (7/53) found it 'Slightly important', 23% (12/53) deemed it 'Moderately important', 25% (13/53) regarded it as 'Very important', and 17% (9/53) viewed it as 'Extremely important'. These results highlight the diversity of opinions on the significance of privacy in soft robot interaction settings.

Preferred settings. Figure 10 illustrates the results to the question, "In which of these settings would you feel most comfortable interacting with a large soft inflatable robot?" indicating that a quiet, private room, busy public space, and hospital or medical facility are generally the most comfortable setting for interacting with the robot. Specifically, 75% of respondents reported they would feel 'Extremely comfortable' or 'Very comfortable' in a quiet, private room, followed by 50% in busy public spaces and 42% in hospitals or medical facilities. In contrast, social events and workplaces are less favoured, with 58% and 52% of responses falling into the "Not at all comfortable" or "Slightly comfortable" categories, respectively.

5 DESIGN AND IMPLEMENTATION

Our SquishiSense prototype features an inflatable body standing at a height of 2 metres, a smiling face, and butterfly-like wings. The main body is responsive to external pressures, which can be triggered via a hugging motion or other similar interactions. Responsive feedback is then conveyed through sound and light, the behaviours of which are dictated by the intensity of the physical interaction. Our design choices, particularly pertaining to size, shape, and sensory output, were informed by the results of Study 1 (see 4). The body was built by sewing together four panels of Poly Vinyl Chloride fabric, followed by sewing on the wings and face. Refer to Figure 11 for the sewing patterns and dimensions used in SquishiSense's construction. The body houses 2 internal ultrasonic sensors which detect user interaction with SquishiSense, by measuring internal distance changes within the main body. We laser-cut a circular piece of wood, with a diameter of 40cm. We used a sheet of acrylic plastic. This kept a flat bottom on our prototype and allowed us to have a flat surface to put our technology on. It also kept the SquishiSense on the floor and grounded. We decided to use a sheet of acrylic plastic, as it is difficult to break, up to 17 times the impact resistance of ordinary glass. [19] it was also very easy to acquire a large sheet of it.

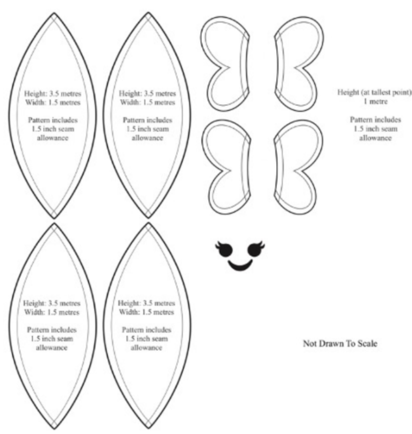

Fig. 11. Patterns for SquishiSense's inflatable body

SquishiSense's design attributes are as follows:

- **Size**: SquishiSense's large size is an important novelty factor, as it encourages full-body, engaging interaction. Study 1 affirmed this, as the median preference for size was approximately 1.85m (see 4). Figure 11 shows the patterns that we used to construct the body, with 4 panels of height 3.5m each. When inflated, this rounds out to be approximately 2m at its tallest point. The circumference at the widest point is approximately 5.5m.

Fig. 12. SquishiSense's fully inflated body

- **Shape**: Study 1 suggested that a round shape with wings and a face was most favourable among participants, so we proceeded as such (see 4).
- **Material**: SquishiSense's body is crafted from a Poly Vinyl Chloride material, while the face is made out of black velvet material.
- **Sensory feedback**: A 5m strip of individually addressable LED light strip is installed within the inflatable body, totalling 300 LEDs aligned along the front seams of SquishiSense. Upon interaction with the body, the LEDs fade to a similar colour in an animated manner from the centre outward, controlled by an Arduino Mega. For audio feedback, a 16W surround sound portable speaker works in tandem with the Arduino Mega. Its high power output ensures sufficiently loud audio feedback, the magnitude of which depends on the interaction taking place.
- **Sensory detection**: Two HC-SR04 ultrasonic sensors are situated inside the inflatable body, detecting variations in distance between the body walls via the use of emitted and then reflected ultrasound waves. The sensors are affixed to the left and right front seams of SquishiSense, which are then fed through into an Arduino Mega.
- **Inflation mechanism**: SquishiSense employs a 680W air blower for inflation, selected for its high airflow rate, which enables rapid inflation upon setup and reinflation following interaction.

5.1 Alternative Designs

Pertaining to SquishiSense's inflatable body, we considered a variety of shapes and sizes, with the aim of developing an engaging, comforting form. Figure 13 demonstrates our initial sketches of potential shapes for SqushiSense, which we presented in our preliminary study to gather user feedback (see 4). As stated above, shape F was most favoured in terms of comfort and engagement.

We considered alternate materials for the main body of SquishiSense. Although PVC ranked 7/10 in terms of comforting textures, it is the most feasible and hygienic – with a problem score of 0 according to Figure 14. Figure 14

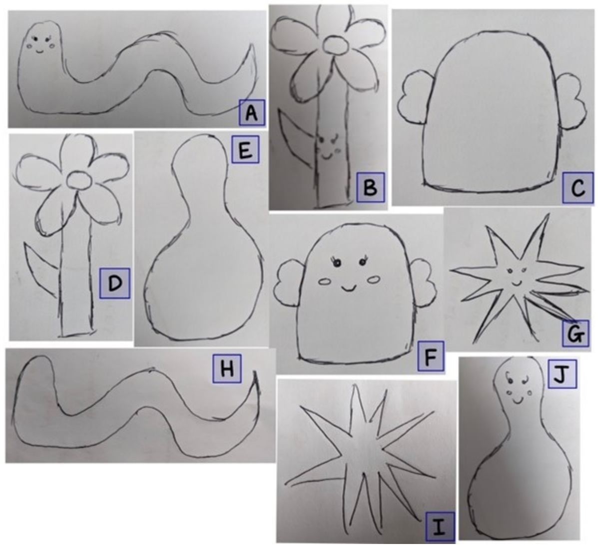

Fig. 13. Initial sketches for SquishiSense's shape

illustrates the reasons for why alternate materials were not chosen for SquishiSense's main body. The score represents the number of problems identified with the material.

Rank according to Study 1	Material	Too heavy/rigid to inflate	Too opaque for light to pass through	Not waterproof: Hard to swipe down/clean	Flammable	Less favoured than PVC according to Study 1	Score
7	***PVC***	✗	✗	✗	✗	***N/A***	***0***
1	Silk	✓	✓	✓	✓	✗	4
2	Cotton	✗	✗	✓	✓	✗	2
3	Velvet	✗	✓	✓	✓	✗	3
4	Wool	✗	✗	✓	✓	✗	2
5	Felt	✗	✓	✓	✓	✗	3
6	Denim	✓	✓	✓	[*]	✗	3
8	Rubber	✗	✓	✗	[**]	✓	2
9	Velcro	✓	✓	✓	✓	✓	5
10	Metal	✓	✓	[***]	✗	✓	3

[*] Denim is flammable but less prone to catching fire compared to other materials on the list
[**] Depending on the rubber used, it may or may not be flammable
[***] Depending on the metal, it may or may not be waterproof

Fig. 14. Problems with Alternate Materials

Our initial patterns for SquishiSense had a height of approximately 2m as opposed to 3.5m. When inflated, the height at the tallest point was 1.2m, suggesting the need for much larger panels.

In the early stages of development, our initial approach to interaction detection involved the use of a basic air pressure sensor, specifically the MPX5700AP. However, upon evaluation, the sensor's readings were found to be insufficiently accurate for our purposes. As a result, we transitioned to a more precise barometric air pressure sensor, the Adafruit MPRLS. Although this sensor resolved the issues of accuracy, the pressure within the inflatable system was determined to be excessively noisy for practical use in reactive feedback. Consequently, we sought an alternative approach. We

Fig. 15. *Left* – the main body of SquishiSense. *Right* – the main body of a previous prototype. For reference, the person in the picture is 5 foot 10 inches tall.

ultimately chose to utilise distance measurements for interaction detection, as this method circumvented the noise issues observed in the previous approach. Various options for distance measurement were considered, including Time-of-Flight (ToF) sensors, which rely on lasers to accurately measure distances. However, ToF sensors are susceptible to inaccuracies in high external light conditions, and thus were deemed unsuitable for our project. Infrared sensors were another potential option, but their limited range and vulnerability to disruption from external light sources led us to eliminate this method as well. Ultimately, we selected ultrasonic sensors, and our subsequent prototyping confirmed the efficacy of this choice. To achieve optimal sound output, we considered several approaches that could be used in conjunction with the Arduino microcontroller. A recurring challenge involved striking a balance between audio quality and volume. After multiple rounds of prototyping, we prioritised achieving a sufficiently loud volume to counteract the noise generated by the air pump, even if this came at the expense of audio quality. To this end, we employed a 16W speaker and an SD Card Reading Module, which enabled us to attain the desired audio amplitude and support flexible, long-format audio data, respectively. Regarding the microcontroller, our initial prototyping began with the use of an Arduino Micro. However, upon integrating the SD Card Reading Module, we determined that the Arduino Micro's SPI support was inadequate, prompting an upgrade to the Arduino Uno Rev3. As development progressed and we incorporated a high-density (60 LEDs/m) individually addressable light strip, the Arduino Uno Rev3's limited RAM became an issue. Consequently, we transitioned to the Arduino Mega, which offers four times the dynamic storage capacity, making it the ideal choice for our microcontroller.

6 STUDY 2: DEVICE EVALUATION

We conducted a user study to evaluate how interacting with SquishiSense affected participants' moods.

6.1 Participants

In this study, we employed 15 participants, comprising 7 females and 8 males, who were fellow university students representing a diverse range of faculties. The participants were recruited using a combination of convenience and snowball sampling methods. The majority (n=9) were selected through convenience, as we advertised our study on social media platforms, resulting in an accessible and proximate sample of individuals. The remaining participants (n=6) were acquired through snowball sampling, with participants referring others whom they believed could offer valuable insights to the study. Among the participants, 6 were unfamiliar with inflatable robots, 8 were somewhat familiar, and 1 was familiar with inflatable robots.

6.2 Group sizes

To ensure each participant would have sufficient time and space to interact with SquishiSense, we split up our study into 3 blocks, whereby 5 participants interacted at a time for each block.

6.3 Study design

Our study was divided into three parts: a pre-study questionnaire (including heart-rate measurement), a 5-minute period for users to interact with SquishiSense, and a post-study questionnaire (also with heart-rate measurement). The study was conducted in a moderately busy room within a university building to simulate a real-life environment where we propose SquishiSense might be used, such as enclosed public spaces. This approach was chosen to evaluate any changes in mood following the 5-minute interaction with SquishiSense and to gather feedback on the user experience. The study aimed to assess the impact of interacting with SquishiSense on participants' moods, with the selected environment providing contextual relevance:

6.3.1 A pre-study questionnaire. Participants were asked to rate their mood on a scale of 1 to 10, with 1 being very low and 10 being very high. Participants' heart rates were recorded.

6.3.2 Interaction with SquishiSense. Participants were encouraged to interact with SquishiSense. We did not encourage any particular interaction styles. A Wizard of Oz study was chosen as opposed to using the touch-detection technology, so we used:

- Remote controlled lights: When users touched SquishiSense, we turned on the internal LED lights and made it change colours so long as there was at least one user touching it. When users removed their touch, we turned off the light.
- Remote control sound: When users touched SquishiSense, we turned on a speaker playing relaxing music. When users removed their touch, we turned off the music.

We opted for a Wizard of Oz study as the touch detection technology had not yet been calibrated to our preferred level of accuracy. to obtain the most accurate results, we manually controlled the lighting and sound. While participants interacted with SquishiSense, we made note of most popular interaction styles and recorded users' comments throughout the interaction.

6.3.3 The post-study questionnaire. This questionnaire can be broken down into the following sections. Note that prior to filling this out, participants' heart rate readings were taken.

- Participants were asked to rate their mood (again).
- Using 5-point Likert scales, ranging from "Not at all" to "Extremely", participants were asked to rate how engaging and comforting they found SquishiSense.
- Using a 5-point Likert scale, ranging from "Not at all comfortable" to "Extremely comfortable", participants were asked to rate how comfortable they felt interacting with SqushiSense in the busy room.
- Using 5-point Likert scales, ranging from "Didn't like it at all" to "Loved it", participants were asked to rate the shape, size, and face of SquishiSense.
- Using 5-point Likert scales, ranging from "Didn't like it at all" to "Loved it", participants were asked to rate the colour-changing and musical features of SquishiSense.
- Finally, participants were asked for any feedback and additional comments on their experience.

6.4 Results

6.4.1 Observations of interactions. All 15 participants hugged SquishiSense, making it the most popular style of interaction. 11 participants presented the behaviour pattern of punching, then hugging. Participant 4, who exhibited this behaviour, said they did this "to check if [SquishiSense] was sturdy". Other popular styles of interaction included leaning on (9/15 participants), playing with the wings (8/15 participants) and walking around it (11/15 participants). Participant 8 said "this made my week" while participant 11 said "I feel so much better".

Participant 7, although initially hugging SquishiSense, spent the majority of the 5-minute interaction time punching and kicking the robot. They said they found the experience "really fun".

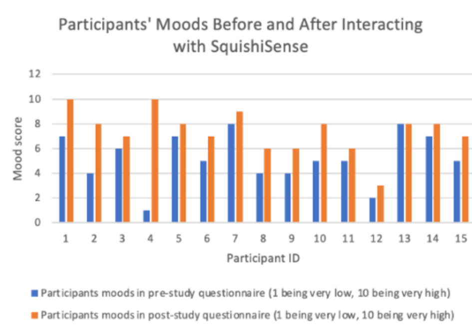

Fig. 16. Participants' moods before and after interacting with SquishiSense

6.4.2 Change in mood. 14/15 participants' moods increased after interacting with SquishiSense. Participant 13's mood remained constant. The most drastic change in mood was reported by participant 4, whose mood increased by 9 points. The average change in mood was +2.2. Results of the paired-t test indicated that there is a significant large difference between Before (M = 101.2 ,SD = 18.3) and After (M = 89.7 ,SD = 15.2), t(14) = 3.9, p = .002.

6.4.3 Change in heart rate. 14/15 participants' heart rates lowered after having interacted with SquishiSense – which could indicate that participants felt calm and comfortable [2]. The most significant decrease in heart rate was recorded

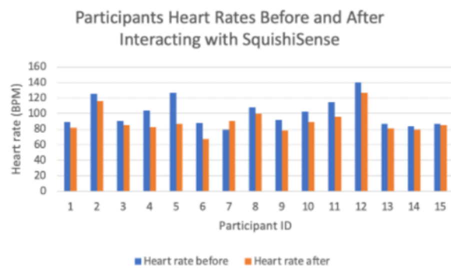

Fig. 17. Participants' moods before and after interacting with SquishiSense

by participant 5, whose heart rate dropped by 40 BPM (beats per minute). Participant 5's primary style of interaction was hugging, followed by leaning on.

Participant 7's heart rate increased following interaction with SquishiSense. Their primary style of interaction was punching and kicking the robot, which could indicate excitement [15]. Their mood also reportedly increased by 1 point on the 10-point Likert scale.

Overall, the average change in heart rate was -11.5 BPM.

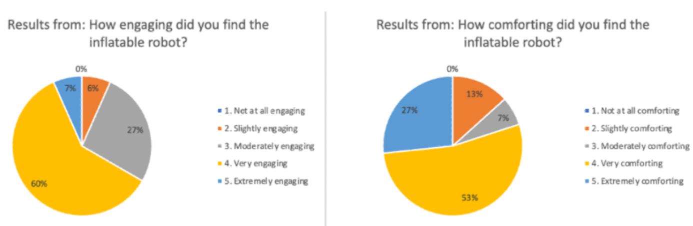

Fig. 18. Results from how engaging and comforting users found SquishiSense

6.4.4 *User feedback on engagement and comfort.*

67% of participants found the inflatable at least "Very engaging" and 80% of participants found the inflatable at least "Very comforting".

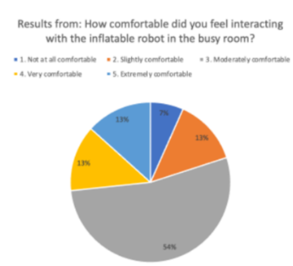

Fig. 19. Results from how comfortable users felt interacting with the inflatable robot in the busy room

6.4.5 User feedback on setting of study. The modal value for level of comfortability was "Moderately comfortable", with the results skewed towards a higher level of comfortability. 26% of participants reported a comfort level of at least "Very comfortable", 13% reported feeling "Slightly comfortable" and 7% reported feeling "Not at all comfortable".

Similar to Study 1 (see 4), these results highlight the diversity of opinions on the significance of privacy in soft robot interaction settings. This study confirms our belief that SquishiSense is best situated in a busy or private room, with the data skewed towards higher levels of comfortability in the busy room. In contrast, some participants reported not feeling comfortable in this setting, with a preference for somewhere more quiet. Specifically, participant 13 said "there were too many people around [which] made me not want to spend as much time with [SquishiSense]. I'd prefer a quiet room".

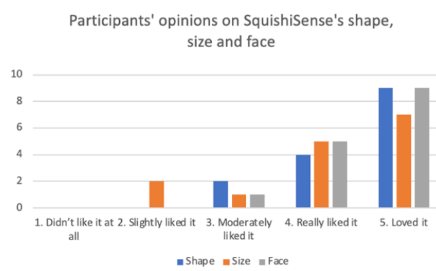

Fig. 20. Results from how users' opinions on SquishiSense's shape, size and shape

6.4.6 User feedback on SquishiSense's shape, size, and face. Users had very positive feedback on the shape, size, and face of SquishiSense:

- **Size**: 12/15 participants at least "Really liked" the size, with 7/15 reporting they "Loved it". 2/15 "Slightly liked it", making the size the most controversial feature.
- **Shape**: 9/15 participants "Loved" the shape, 4/15 "Really liked it" and 2/15 "Moderately liked it"
- **Face**: 9/15 participants "Loved" the face, 5/15 "Really liked it" and 1/15 "Moderately liked it"

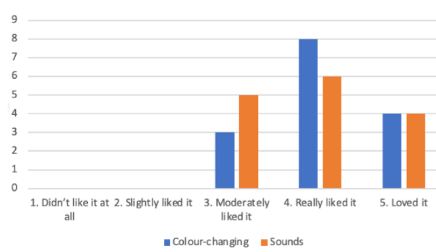

Fig. 21. Results from users' opinions on SquishiSense's responsive colour-changing and musical output

6.4.7 User feedback on SquishiSense's colour-changing and musical features. Users had very positive feedback on the colour-changing and musical output of SquishiSense:

- **Colour-changing**: 8/15 participants "Really liked" this feature, 4/15 "Loved it" and 3/15 "Moderately liked it.
- **Musical output**: 6/15 participants "Really liked" this feature, 4/15 "Loved it" and 5/15 "Moderately liked it".

The colour changing feature was enjoyed more by participants: 12/15 at least "Really liked" the colour changing feature and 10/15 at least "Really liked" the musical output.

6.5 Additional comments and feedback

- **Size**: Although 12/15 participants at least "Really liked" the size, we received feedback both for making SquishiSense bigger, and smaller. Participant 4 said it was "too wide to get a good hug" while participant 5 said to "make it slightly bigger", and participant 6 said they'd like it to be "obnoxiously large" while participant 7 said it was "a bit too big to get a proper hug". For every comment about enlarging the size, we received a comment about shrinking the size, so we believe our design strikes a good medium.
- **General appearance**: Participant 15 said the shape and face were "very welcoming" while participant 10 said it was "very cute".
- **Material**: Participants 8 and 9 said they'd prefer a softer material. We justify our choice of material in [].
- **Light**: Participants 2, 6, 8 and 10 said they enjoyed the "rainbow" lights. Participant 13 said the lights were "perfect".
- **Fan sounds**: Participants 4, 9, 12 and 15 reported that the fan was "too loud". Participant 3, however, said they enjoyed the "white noise" produced by the fan.

6.6 Summary of results

Section	Key results
Change in mood	Interacting with SquishiSense improved participants' moods. The average change in mood was +2.2.
Change in heart rate	The average change in heart rate was -11.5 BPM, suggesting SquishiSense relaxed our participants
User feedback on engagement and comfort	67% of participants found the inflatable at least "Very engaging" and 80% of participants found the inflatable at least "Very comforting".
User feedback on the setting of the busy room	The modal value for level of comfortability was "Moderately comfortable", with the results skewed towards a higher level of comfortability.
User feedback on SquishiSense's shape	13/15 participants at least "Really liked" the shape
User feedback on SquishiSense's size	12/15 participants at least "Really liked" the size
User feedback on SquishiSense's face	14/15 participants at least "Really liked" the face
User feedback on SquishiSense's colour-changing	12/15 at least "Really liked" the colour changing feature
User feedback on SquishiSense's musical output	10/15 at least "Really liked" the musical output

7 DISCUSSION

Our second study (see 6) presents empirical evidence illustrating the efficacy of SquishiSense in enhancing the mood and relaxation levels of participants. The data substantiates a notable improvement in mood, with a mean increase of +2.2 on a scale of 1-10, and a substantial reduction in heart rate, averaging -11.5 beats per minute (BPM). The results from our questionnaire, as well as Wizard of Oz study, indicate its potential for further applications in the fields of emotional support and stress relief. We have identified several directions we plan to investigate in the future.

7.1 Customisation possibilities

While the majority of participants enjoyed the shape, size, and face of SquishiSense, some expressed preferences for alternative sizes. Future work could explore customisable or modular designs, allowing users to adjust the robot's size and shape to their preferences, which may further enhance their emotional connection and comfort.

7.2 Material experimentation

A few participants indicated a preference for a softer material for SquishiSense. Future studies could involve testing various materials to balance durability, softness, and comfort, potentially enhancing the user experience.

7.3 Improving touch-detection technology

The Wizard of Oz study used in our research was an effective approach to measure mood changes during interaction with SquishiSensi. Future work could focus on refining and integrating the touch-detection technology to provide a more seamless and autonomous interaction experience for users.

7.4 Evaluating SquishiSense in different settings

Our study was conducted in a busy room, and while the majority of participants reported feeling comfortable in this setting, some expressed a preference for a quieter environment. Future work could involve comparing user experiences with SquishiSense in different settings, such as private rooms, quiet public spaces, or outdoor environments, to understand how context affects interaction. We propose venues such as art galleries and shopping centres, as our findings in Study 2 (see 6 suggest these would be appropriate settings for SquishiSense.

7.5 Investigating long-term effects

Our study focused on immediate mood changes after a 5-minute interaction with SquishiSense. Future work could explore the long-term effects of using SquishiSense for stress relief, emotional support, or relaxation, as well as any potential habituation to its effects.

7.6 Integration with biofeedback sensors

Future research could explore the integration of biofeedback sensors, such as heart rate monitors or skin conductance sensors, with machine learning algorithms to create a more personalized and emotionally intelligent robot. By gathering real-time data on the user's emotional state and adapting its behaviour based on previous user interactions, SquishiSense may be able to better cater to user's specific needs and emotions. This would create a more personalized and dynamic interaction, further strengthening the emotional bond between the user and the robot

7.7 Studying the impact on specific populations

Future work could examine the effects of SquishiSense on specific populations, such as children with autism, individuals with anxiety disorders, or elderly people experiencing loneliness. This research could help identify and optimize the potential therapeutic benefits of the robot for various user groups.

8 CONCLUSION

In conclusion, this paper answers our research question, exploring how giant, interactive, inflatable robots can affect users' moods by providing compelling evidence of impacting it in a positive manner: mood was seen to increase by 2.2 on a 1-10 scale and a mean heart rate saw a decrease of 11.5 BPM. By examining various aspects of the robot, such as its shape, size, appearance, and interactive features, this paper has contributed valuable insights into the development of emotionally supportive and stress-relieving soft robotic systems. Moreover, the research has identified numerous avenues for future exploration, including customisation possibilities, touch-detection technology, evaluation in diverse settings, long-term effects, integration with biofeedback sensors, and potential impact on specific populations. These findings not only showcase the promise of SquishiSense as an innovative tool for emotional support and stress relief but also lay the groundwork for further research in this emerging field, ultimately paving the way for more effective and personalised human-robot interactions.

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9 APPENDIX

9.1 Teamwork and diversity

Fig. 22. The Dream Team

In our team, we recognised the importance of understanding that each member's strengths contribute to a more effective collective. To ensure that all of our skills were utilised and appreciated, we assigned both 'main' and 'sub' roles for each team member, reflecting their top two strengths. This meant that if someone couldn't attend a team meeting, there would always be someone to communicate the progression in each area.

The roles assigned were as follows:

- Ella: Writing, drawing
- Tegan: Sewing, hardware
- Sam: Writing, software
- Dan: Hardware, software
- Vasudev: Video-making, general technology, writing

Our collaborative approach involved those in the writing roles (Ella and Sam) writing assigned sections, seeking feedback from staff, and then swapping roles to address comments, thereby incorporating multiple perspectives. Tegan and Dan, responsible for sewing the body and technology respectively, worked closely to ensure seamless integration between the inflatable body and the technology. Vasudev, with his multifaceted strengths, contributed to both writing and technology, while also creating the project's video.

We prioritised regular in-person meetings to update each other on individual progress and set weekly goals. Additionally, we stayed connected via Whatsapp. When team members were not in Bristol, we met remotely via Teams or other platforms. Specialised sub groups, such as Ella and Sam for writing, or Vasudev, Dan and Tegan for constructing the device, also held separate meetings. This way, Vasudev was also able to record videos through the construction process to be used in our video.

To maintain an inclusive environment, even when a team member could not attend a meeting. they made an effort to join via Teams or provide a progress update. This meant that every voice was heard and valued.

Throughout the project, we supported one another, especially during difficult moments such as when our robot was built too small (this was very disheartening), or when technical issues kept persisting (Dan went through many methods to detect touch). Our dynamic, which embraced diversity and inclusivity, allowed us to work effectively, complement each other's strengths, and uplift each other.

9.2 Video link

https://youtu.be/C-RpwzcRssU