ABSTRACT

Title of thesis: ENABLING ON-BODY COMPUTING USING A TRACK-BASED WEARABLE

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We are seeing an increasing trend in the number of computing devices attached to the body which provide a myriad of data along with additional interaction mechanisms and haptic feedback from these locations. Although this provides more computing locations, the devices are still resigned to stay in those particular locations. We believe that relocatable wearables can reduce the number of devices that the user has to keep track of, while also providing dynamic data by moving around the body. Some attempts have been made to build relocatable wearables, but these attempts are either too bulky or make the use of unreliable and slow locomotion mechanisms.

In this thesis, we present Calico, a miniature wearable robot system with fast and precise locomotion for on-body sensing, actuation, and interaction. Calico consists of a two-wheel robot and an on-cloth track system or "railway," on which the robot travels. The robot packs an IMU, a battery and an onboard microcontroller that supports wireless BLE communication. The track system has multiple branches

that extend to key areas of the human body, allowing the robot to reach the front and back of the torso, shoulders and arms, and even lower body areas such as legs. The track system also includes rotational switches, or "railway turntables," enabling complex routing options when diverging tracks are presented.

We introduce the system design of Calico and report a series of technical evaluations for system performance. To illustrate potential use cases, we present a suite of applications, including remote medical usage for chest auscultation, body posture tracking for training and exercise, a wearable walkie-talkie, and a robot companion living on-body.

ENABLING ON-BODY COMPUTING USING A TRACK BASED WEARABLE

by

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Table of Contents

List of Figures

Chapter 1: Introduction

The more you can do by

intuition the smarter you are;

the computer should extend

your unconscious.

Mark Weiser

There was a time when computing devices manifested themselves in cumbersome forms involving large rooms and days of computation to solve simple problems[1]. Regardless of the fact that computers such as these still allowed humankind to put a man on the moon, the future of computing couldn't revolve around large mainframe computers that were only accessed when their processing power was needed. The transistor and subsequently the computer, would eventually change the world. But the form factor that they occupied in the early days wouldn't enable them to trickle down through day-to-day life. For computers to change our lives in a meaningful manner however, something else was required. Eventually as computers get smaller and more powerful, they will be able to weave into our lives just like the spoons we eat our food with, and the tables on which we work. This vision of ubiquitous and

[1]Some parts of this thesis, along with the figures are derived from a submission made to UIST 2021.

pervasive computing was famously expressed by Mark Weiser [1].

The purpose behind this vision is to build human intuition in ways that are not possible without the use of a small computing device. Throughout our lives we develop our intuition in various ways. In most scenarios, this intuition is developed by receiving and perceiving data in various forms. Usually, the people around us perform this data perception that allows us to build intuition. With small computing devices, this data perception can be shifted from a human to a computer. For instance, let's consider a person that wants to increase their fitness levels. A common approach is to start counting daily steps. Prevailing health advice from the medical community provides a 10000 step goal that a lot of people try to achieve. Tracking your step goal manually by counting every step would be extremely cumbersome. In order to offload this data perception from the brain, a small pedometer is used to track our steps. This perceives the data needed to develop intuition regarding our daily activity goals.

As a manifestation of this endeavour, wearable devices such as fitness trackers and smartwatches have been widely adopted in our daily lives for both health monitoring and interaction purposes. We are also witnessing the trend of wearable device minimization, where both the size of these devices and their distance from our bodies are reducing [2–5], suggesting a promising future when miniature wearable devices may co-exist with us 24/7 for both sensing, actuation, and interaction. However, most wearables to date assume that their locations are fixed only to a particular location on our body. In reality, the human body offers various types of biodata from different areas. For example, it is best to monitor breathing from the front or back of one's upper body [6], while the wrist can be ideal for sensing hand activities such as typing and writing. Different body areas are also suitable for different types of interactive tasks. For example, the neck and ear can be good for voice commands, while the forearm offers ample skin area for hand input [7]. Thus, if a user wants to interact with or acquire physiological information from different body areas, they are destined to wear multiple devices in various form factors, and on numerous areas of the body.

Recent work, such as Rovables [8], proposes an alternative way of wearable technology, where the locations of these devices can be flexible. For example, Rovables can move on one's clothing to nudge different areas of the torso for distinct notifications; multiple Rovables can also park at body joints for motion tracking. Although Rovables [8] demonstrates promising uses, its magnetic-roller-based locomotion mechanism only offers limited climbing speed and precision, due to the complexity and flexibility of clothing material. To build a system capable of providing useful data and interaction points at different locations of the body, it's imperative to build a reliable locomotion mechanism. On top of reliability it's also important to consider the precision of the localization mechanisms employed by the wearable to detect the current location of the wearable. When an imprecise mechanism is used to detect the current location and collect data from said location, the sensor data might no longer be usable. This defeats the purpose of data collection.

In this paper, we aim to resolve this challenge with Calico, a relocatable wearable with an on-cloth track system. With Calico, robots can transit long distances across different areas of the body, such as from one's forearm to the back, or from the thigh to the chest, regardless of the material deformation or the seams between different pieces of cloth. The locomotion is also fast and accurate, with a speed of up to 22 cm/s and an accuracy of up to 4mm. In doing so, Calico accommodates common daily activities and supports the one-device-for-all scenario: for instance, it can stay on the wrist as an activity tracker while the user is running, and quickly climb to the neck to act as a walkie-talkie when the user starts talking.

The key to Calico is an on-cloth track system, inspired by the railways, on which the wearable transits. In a railway system, rail tracks are used as dedicated pathways to navigate various terrains; railway turntables are used as central hubs to allow trains to switch lanes. In a similar vein, Calico stitches custom soft tracks directly onto clothing which then function as expressways to overcome the material's natural deformations. Calico also includes rotational switches, like railway turntables, to allow on-cloth track switching and to ensure that all critical areas of the human body are reachable. Calico's design closely considers comfort and appearance, making sure that the wearable has no direct contact with human skin while moving, and that the tracks are color-matched to the clothing.

In the following material, we detail the design consideration of the Calico system. We report the implementation and the system performance with a series of experiments. To highlight the potential of Calico, we showcase a number of applications: see Figures 5.1-5.6. We conclude with a discussion and design guidelines for future relocatable on-body wearables.

Chapter 2: Related Work

Our work builds upon the concepts of on-body sensing and interaction, body area networks, on-cloth wearables, and locomotion mechanisms for relocatable wearables.

2.1 On-body sensing and interaction

In the field of HCI, researchers have explored biosignal sensing and on-body interactions at different locations on the human body [6]. For example, work has been done to detect touch coordinates or distinguish between ways of typing by placing bio-acoustic [7, 9] or electromagnetic sensors [10–12] near the wrist. Spatial information can also be offered at the wrist using skin-drag [13] or pin-based actuators [14]. Researchers have also explored finger [15, 16] or fingernail [2, 3, 17] worn devices to recognize fine-grained typing activities or even as miniature displays for personalized notifications. Apart from the upper limbs, non-speech signals can be detected from other parts of the body. For example, MusicalHeart [18] monitors one's heartbeat using sensor-equipped earphones; Bodybeat [19] and BodyScope [20] use microphones on the neck to recognize the sounds produced in the throat. These on-body wearables require direct skin contact, but their form-factors are often sizeable.

To reduce the size of wearable devices for comfort and ease-of-use, researchers have explored wearables in a new form-factor called electronic skins or E-skins [4]. For example, iSkin [21], Multi-Touch Skin [22] and PhysioSkin [23] propose flexible and stretchable biocompatible sensors for touch sensing. DuoSkin [5] achieves touch sensing using gold metal leaves that balance functionality and aesthetics. Holz et al. [24] discuss the concept of hiding sensors directly under the human skin, as well as the applications of such a process. E-skins aim to minimize the distance between the sensor and the human body, but the locations of these sensors, once applied to the body, are fixed. They also have a limited lifetime, requiring daily intervention by the user.

2.2 Body Area Networks

When multiple sensing and interaction devices are deployed on a body, creating seamless channels that can be used by the devices to communicate between each other and provide meaningful information is important. This direction is pursued by researchers studying Body Area Networks (BANs). Paschalidis et. al. propose a method [25] to detect the posture of a user using multiple sensors connected to BAN. Motion data can also be used to detect sports performance and provide information to increase the skills of the user [26, 27]. Extensive work has been done to classify the activities being performed by a user using a combination of multiple accelerometers in a BAN [28–30]. As the amount of data collected in a BAN can be easily weaponized or misused, work is being done to establish secure protocols to maintain data privacy [31–34].

2.3 On-cloth wearables

Clothes, being essentials that come into contact with many parts of the human body, have naturally been studied substantively in HCI and used as platforms for novel interactions [35–41]. For example, various touch input methods have been proposed using sleeves [36, 37, 39], pockets [42], button snaps [43], headphone cords [35], and zippers [44]. Like E-skins, on-cloth sensors reduce the size of the sensing devices; however, on-cloth wearables do not require the user to re-apply these sensors regularly as they can be fully integrated into the garments. Nonetheless, most on-cloth wearables still require sensors to be fixed to certain locations on the clothing, thereby limiting the sensing and interaction space.

2.4 Locomotion mechanisms for relocatable wearables

In recent years, researchers have proposed new wearable displacement methods, where sensors and actuators are not fixed to one place, but can be relocated. For example, Rubbot [45], Clothbot [46], CLASH [47], and Rovables [8] employ different types of cloth-pinching mechanisms that allow wearables to move freely on cloth substrates without modifying the material. Such free climbing capabilities, however, come with trade-offs. To prevent falling from the human body, these devices need to firmly grasp and deform the fabric, making locomotion slow and inaccurate. The choice of clothing substrates is also limited, often only to thin and flat material.

To avoid these issues, we decided to alter the clothing in a careful, non-intrusive manner to reap the benefits of increased locomotion and localization performance. To the best of our knowledge, the only work that is similar to ours in concept, is [48], in which researchers built a rail system attached to the body using a belt. However, the implementation is sizeable, with the robot only travelling in a single dimension along the arm. In our design, we aim to drastically reduce the size of the robot, make the movement much faster, increase the number of areas that the robot can move to, and also improve the social acceptance of the system by blending the tracks into the user's clothing.

Chapter 3: Calico System

We now detail the design and implementation of our system. We start with our design considerations.

3.1 Design considerations

Several key considerations and constraints dictated the design of the Calico system.

1. **Fast speed**: Different sensing or interaction use cases may happen all across the human body. Thus, it is crucial that our device is capable of a high speed such that it is responsive, and can quickly navigate on-body and accommodate different scenarios.

2. **Robust movement**: The human body is rarely stationary. Thus our device needs to remain functional and stay on-cloth, when the user performs different activities such as walking, jogging, and jumping.

3. **High reachability**: Since multiple body areas can be useful for sensing and interaction, our system should be able to reach all these critical areas.

4. **High precision**: Some applications, such as chest auscultation or breathing

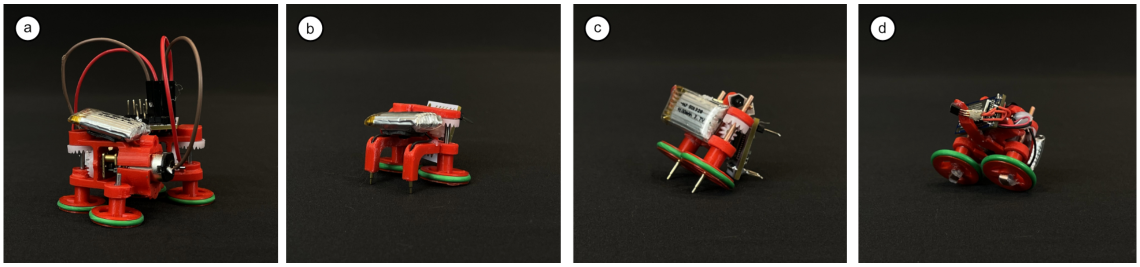

Figure 3.1: The different design iterations of Calico. a) The proof-of-concept with 4 wheels and 2 Pololu Micro Metal Gearmotors. b) Switching to a smaller motor with a different gear assembly. The overhangs would easily get caught on wrinkles in the clothing. c) Switching to a copper shaft to avoid the overhangs but still create electrical contact with the turntable. d) Switching to dual motor drive and magnets with copper plates to increase the speed and the climbing capacity.

detection, require the device to move precisely to a certain body area for accurate data collection. Thus, it is essential that our system knows its current location in relation to the human body and can reach the destination in a fine-grained manner.

5. **Low weight and small form factor**: Since the wearable will be worn daily, it is important to maintain a small footprint with a low weight to minimize the burden placed on your body.

6. **High payload capacity**: Different applications may require the use of various sensors and actuators. It is ideal to have a payload high enough to carry sensors that enable such applications.

7. **Aesthetic flexibility and social acceptance**: As an on-cloth wearable device, we should also consider its social acceptance. We aim to make the system unobtrusive, comfortable to wear, and also consider aesthetic flexibility.

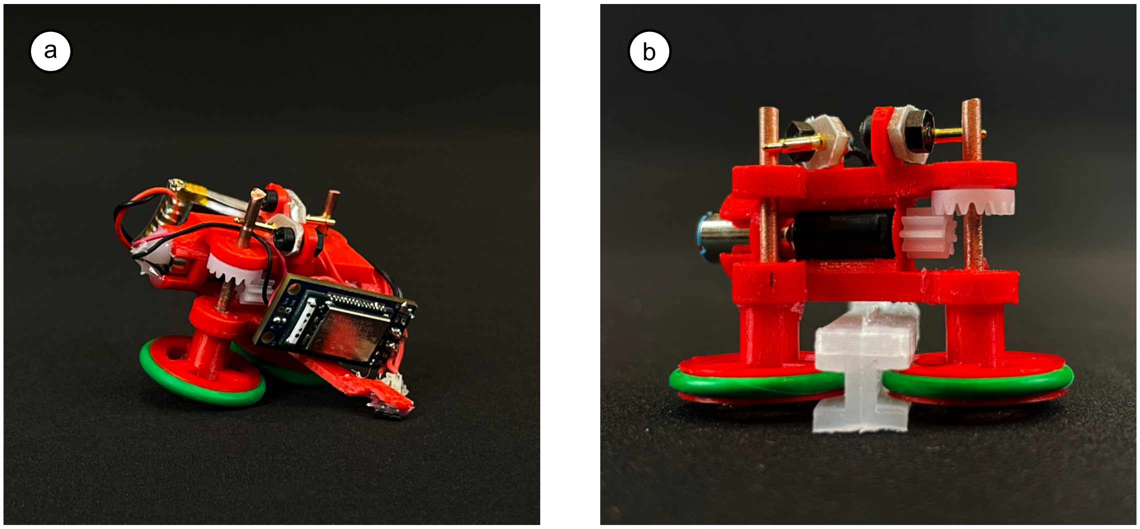

Figure 3.2: a) The Calico bot. b) The latching mechanism used by the Calico bot to move along the track.

3.2 The Bot

Figure 3.1 presents the early prototypes of the bot with an iterative design process. All design centers around the idea of "railways" on cloth–Calico's core climbing mechanism. To ensure reliable climbing while minimizing the impact to the wearer, we design the robot so that the wheels do not have direct contact with the human body but latch on the track system.

Our initial prototype has four wheels to ensure a stable grasp of the track (Figure 3.1a). The bot also has a ball bearing at its center, which allows the front and back sections to move somewhat independently from each other. The bot can move along tracks with curves in parallel to its chassis. However, the four-wheel configuration does not have the flexibility to bend along its central axis, preventing the bot from going over curves that are normal to its base, such as those generated from cloth grooves, wrinkles or such as those while moving from the arm to the shoulder. With all four wheels, the size of the bot is also relatively large. Although it was deemed impractical, this initial prototype allowed us to narrow down the required characteristics of our desired system. The pinching mechanism used to latch onto the tracks was found to be promising. We deployed this initial prototype on a 2-core power wire. This also allowed us to identify the required characteristics of the track.

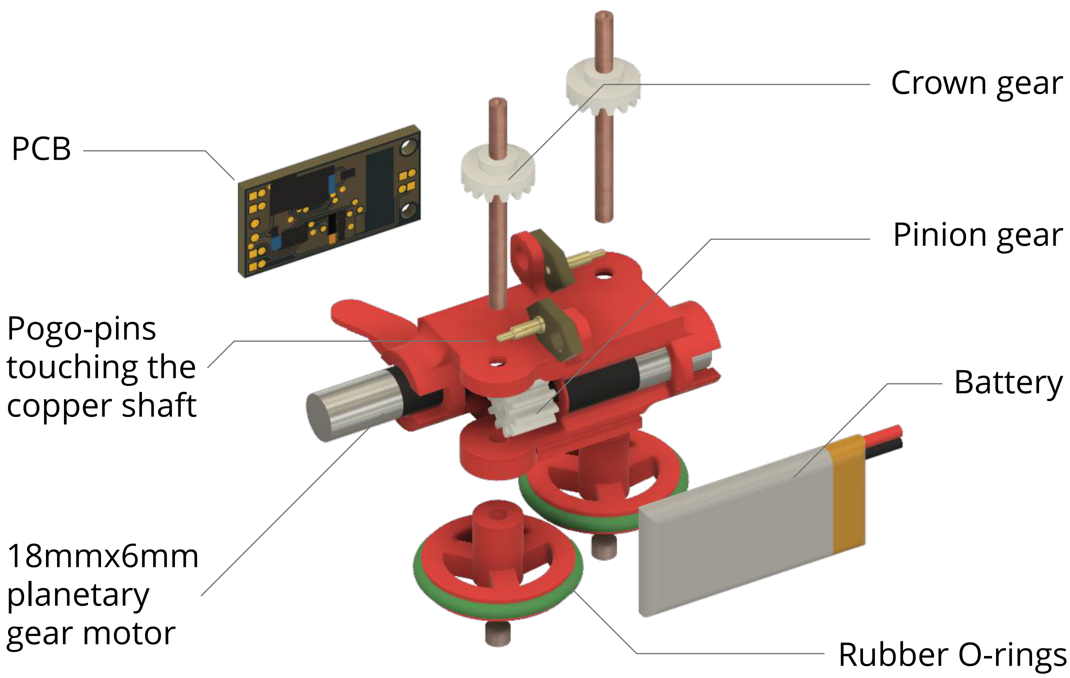

Figure 3.3: An exploded view of Calico

During this design process we also went through multiple other iterations. These iterations were in conjunction with the other parts of the system discussed in future sections. As the bot needs to switch between tracks, the switching mechanism played a central role in our design iterations. Initially, we attempted to mesh gears with a turntable system in order to switch tracks. Meshing gears dynamically in a system would be close to impossible. Next, we decided to use overhangs that house pogo-pins. The pogo-pins would make contact with copper pads on the turntable. These overhangs would easily get stuck on clothing. In order to avoid this, we changed our design to a copper shaft and devised a system to create electrical contact with pogo-pins attached to the bottom of the wheel. Although this iteration performed better than the previous one, the pogo-pins would still easily get stuck on clothing. This required a reduction in height under the wheel. To achieve this height reduction, we replaced the pogo-pins with a copper covered magnetic connector. This would have the additional benefit of making electrical contact easier.

Figure 3.1d shows the final design of our Calico bot. The final design uses the same wheel-track pinching mechanism but employs two independently driven wheels. Each wheel has a diameter of 18mm and is covered with a rubber O-ring to increase the friction with the track. Two 242 rpm, 6mm planetary gear motors, and an additional 2:3 ratio crown gear set were used in concert to drive the two wheels. We use two motors to ensure the bot has enough torque to overcome gravity while also providing payload capacity. The crown gear allows us to install motors parallel to the bot's wheels, which reduces the bot's overall height and lowers the center of gravity. As described above, the magnets act as contact points to drive the turntables, which we will detail in Section 3.4.

Calico is designed with minimization in mind, so we created a custom 2-layer PCB to control the bot (Figure 3.4). The PCB is 13mm x 24mm, with an MDBT42Q on one side (built on the NRF52832 by Nordic Semiconductors) as its main processor, and a DRV8835 dual H-Bridge and an ICM20948 9DOF IMU on the other side — for motor control and onboard sensing, respectively. The MDBT42Q has native

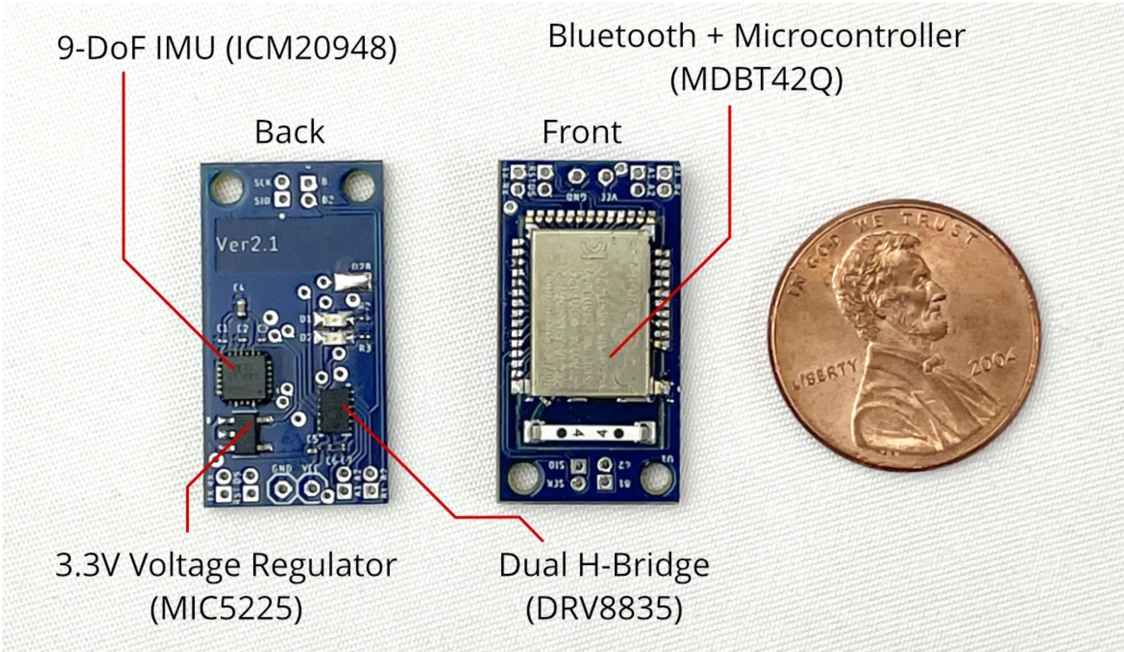

Figure 3.4: Custom PCB designed to maintain a small device footprint.

support for Bluetooth Low Energy (BLE), which is Calico's primary communication mechanism. We also include two A3144 hall-effect sensors at the bottom of the bot used for on-track localization and controlling the turntable, which will be discussed further in Sections 3.3 and 3.4. The bot is powered by a 3.7V 100mAh Li-Po battery with a size of 30mm x 4mm x 13mm. Once assembled, the Calico bot has a size of 42mm x 32mm x 35mm, and a weight of 18 grams. It can carry a 20 gram payload — more than it's bodyweight — and achieve speeds up to 22.7cm/s. We will detail the experiments conducted to evaluate the bot's performance in Section 4.

3.3 The Track

Figure 3.5 is our custom track design. From the user's perspective, the track needs to be lightweight and not present a burden when attached to clothing. It also

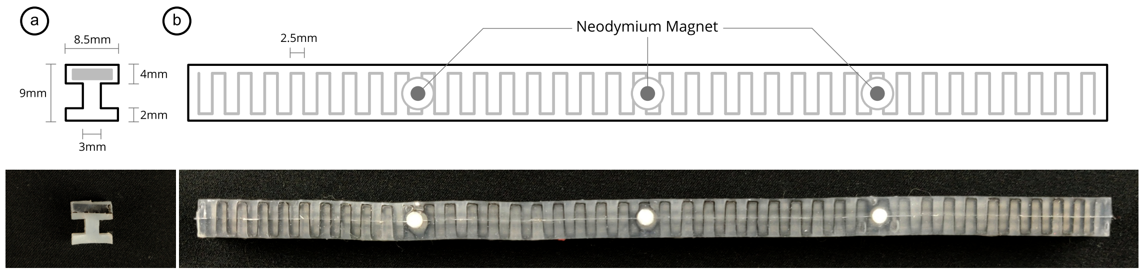

Figure 3.5: Meta-material track design. a) Cross-section of the track. b) Top view of the track with embedded magnets and a live-hinge pattern of the inlay.

has to be flexible to ensure that the movement of the body is not restricted. From the system's perspective, the track needs to be deformable so that the bot's wheels have a sufficient contact area for stable climbing. The pinching area also requires a rigid cover to preventing derailing. Furthermore, the track has to be easy to stitch and be highly durable to withstand standard clothing care procedures.

Figure 3.5a is the section view of the track. A 3 mm height, 3mm thick flexible center wall is sandwiched between two flat panels, one with 4mm by 8.5mm at the top and one with 2mm by 8.5mm at the bottom. When climbing, the two wheels of the bot will engage with the center flexible wall. The top panel is designed to prevent the bot from run over the track. The flat bottom panel offers ample space for stitching.

A major part of the track is molded with platinum cured silicone (Smooth-On's EcoFlex™ 00-50). While experimenting with the molded track, we noticed that the top panel by itself is not sufficient to prevent derail. In fact, the bot would always deform and pinch through the top panel, regardless of its thickness. To solve this, we propose a meta-material track design, with the top panel embedded with a solid live-hinge pattern with 2.5 mm pitch (Figure 3.5b). The inlay maintains the

Figure 3.6: Due to the live-hinge design, the track can be flexed in all directions while still restricting the degree of freedom to keep the wheels of the bot in the crevice.

track's flexibility in all directions while offering a rigid cross-section that cannot be penetrated by the bot's wheels. The inlay is 3D printed with thermoplastic and can almost entirely blend into the track when choosing with the proper color (Figure 3.11).

One benefit of having custom tracks is that we can conveniently include landmarks for precise locomotion. We embed additional cylindrical neodymium magnets (3mm x 2mm) into the track's top with a fixed distance of 50mm between them. This was chosen to maintain fabrication simplicity. The distance can be changed based on the required specification. When the bot moves over one such magnetic landmark, the hall effect sensors installed at the bottom of the bot will pick up the signal.

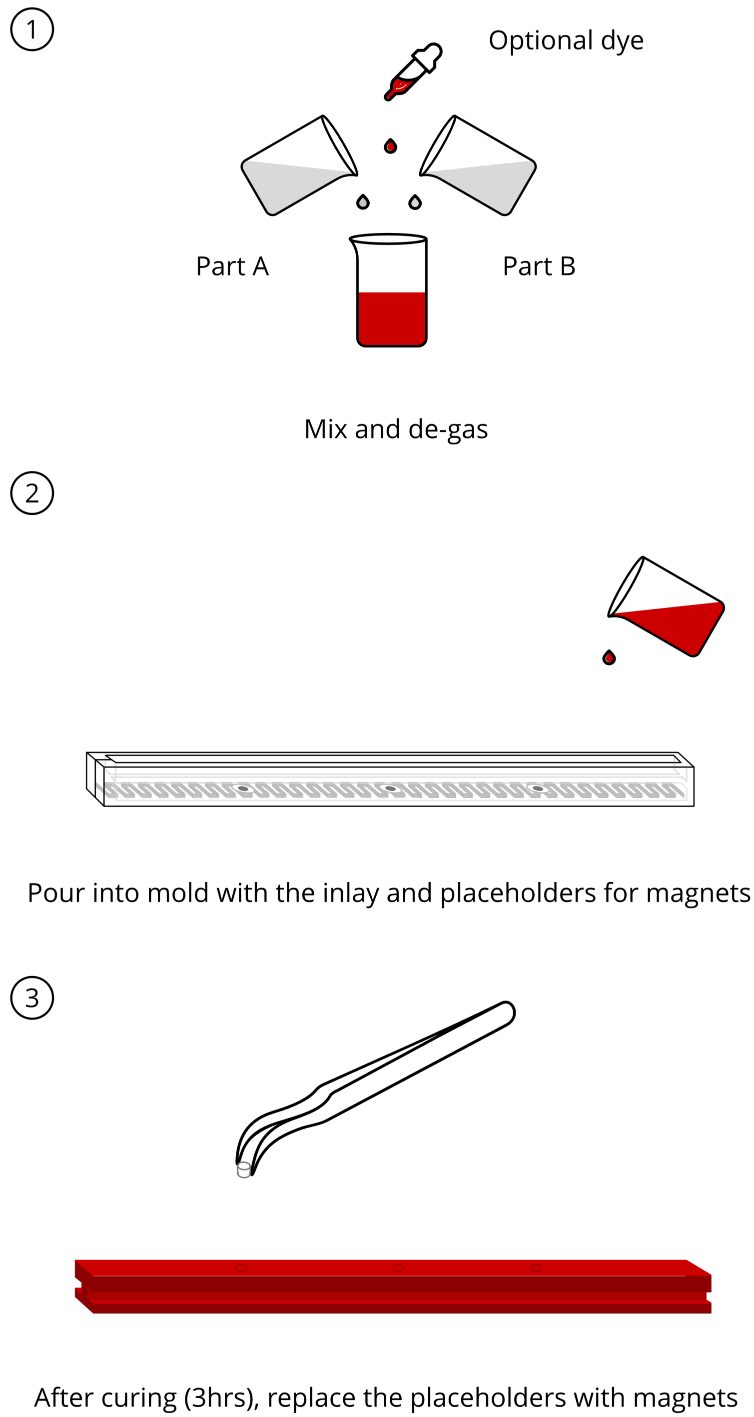

Figure 3.7: Track fabrication procedure

3.3.1 Fabricating the track

The track is fabricated using a 3-step procedure (Figure 3.7). *First*, the two part EcoFlex is mixed and de-gassed. An optional dye can be added at this stage to change the color of the track. *Second*, the silicone mix is poured into the 3D printed mold with a live-hinge inlay and placeholders for magnets. *Third*, the track is cured for 3 hours. After this curing process, the magnet placeholders are replaced with the cylindrical magnets and fixed using a silicone epoxy (Smooth-On SilPoxy™). One piece of such track is 20 cm long. We can connect multiple modular tracks with silicone epoxy for the desired length. The track can also be trimmed into smaller sections for reduced length.

3.4 The Turntable

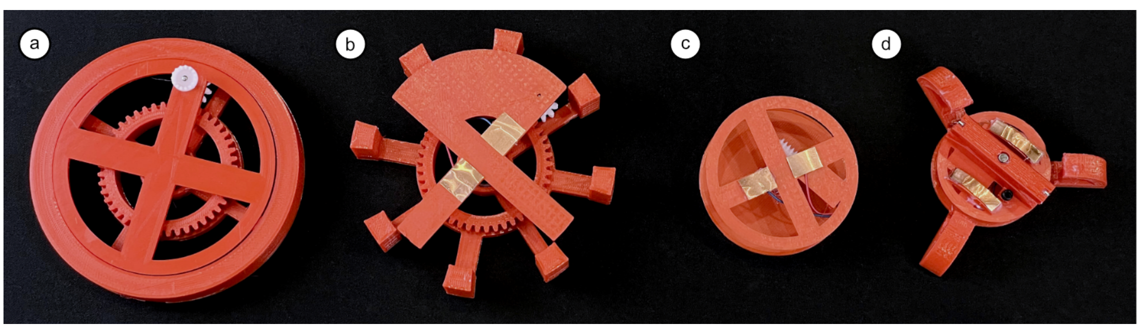

Figure 3.8: From left to right, all the major design iterations of the turntable. a) An extra motor on the bot would latch to the crown gear on the turntable to rotate it. b) Moving the motor from the robot to the turntable to avoid meshing gears as creating electrical contact is easier. c) Reducing the size of the turntable by rotating around an external spur gear instead of an internal spur gear. d) Using a gear train to reduce the size further and adding fixed ramps to allow the robot to reliably move onto the turntable.

The turntable is the last piece of the Calico system, which allows the bot to

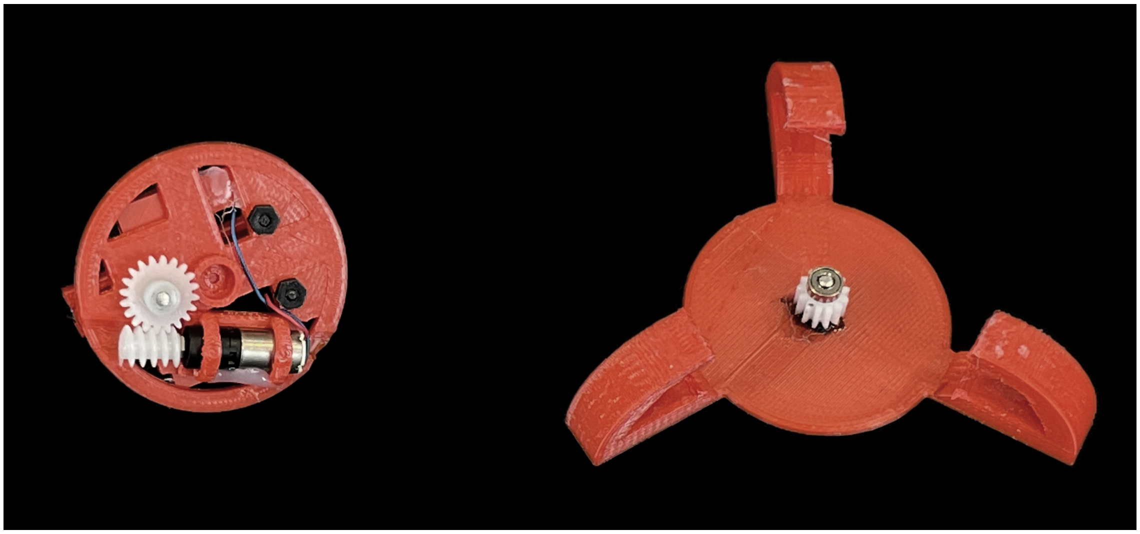

Figure 3.9: The turntable mechanism. When the bot makes contact with the copper pads on top and sends a signal through the motor driver, the rotor rotates around the base, which also rotates the bot.

switch between tracks at specific locations of the on-body network. Similar to the bot design, we went through multiple iterations (Figure 3.8) to minimize its size and the number of required onboard electronics.

Figure 3.8d details the final turntable design. The turntable composes of two main components, the base with a pinion gear at its center and a rotor sitting on its top. The rotor's bottom side holds an off-centered spur gear, which engages between the pinion gear of the base, and a worm gear that is driven by a 1000 rpm 6mm planetary gear motor. The motor's two electrodes extend to the top side of the rotor, with two copper contact leaves and neodymium magnets underneath. When the bot moves onto the small turntable, the bottom of its wheels, which are equipped with a small neodymium magnet and covered by a copper plate, will align with the turntable's contact leaves. The bot's onboard battery and the motor driver will then activate the rotor's motor, which rotates the turntable and hence the robot itself.

Our final turntable design has a diameter of 40mm, excluding the ramp. The base of the turntable can be directly stitched on to the clothing while the rotor top that holds the gear motor is removable. This design reduces the effort for maintenance, as the entire cloth becomes washable once we take off the rotors. The turntable's design allows the inclusion of 6 entry and exit points. The Calico bot can also switch tracks with a high speed when on the turntable. A full 360° rotation of the turntable takes only 0.4s.

3.5 Identifying locations of interest

The use of an on-cloth track system ensures a fast and reliable climbing capability and reduces the localization burden. However, the track design can potentially limit the areas that can be reached by the bot. To diminish the potential impact, we follow suggestions from [6, 49], in which several key areas of interest for on-body sensing was mapped out by conducting user research. As shown in Figure 3.10, we picked the most common points that aligned with the garment of our choice. The current track deployment includes 48 points of interest spread across both arms, both legs, the chest, the back and the stomach area. We also ensured that the track system is not over-complicated and cumbersome. Note that these points of interest can be changed based on the context in which the system will be deployed and the applications it needs to support. At two locations — left shoulder and upper chest — where pieces of track were coinciding with each other, we chose to add turntables

Figure 3.10: Using a track system on the clothing allows us to project the 3D terrain onto a 2D graph structure. The points of interest must be chosen before this projection.

to allow the Calico bot to switch between paths. The turntable configuration can also be customized based on the location and the orientation of the entry and exit points.

3.6 System Control and Localization

3.6.1 Control

The MDBT42Q is flashed with the Espruino[1] bootloader, a JavaScript interpreter for low-power devices. This low energy consumption is achieved by being

[1]Espruino Bootloader - https://www.espruino.com

entirely event-driven. The Calico bot connects to a BLE-enabled device such as a smartphone or a laptop with all communication and control running via a web browser or a web based IDE. With low energy consumption, Espruino's MTU (Maximum Transmission Unit) is 20 bytes. This could have additional constraints to some of our applications, which we will discuss in Section 6.4.

3.6.2 Localization

The track is embedded with small cylindrical neodymium magnets as explained in Section 3.3.1. The hall effect sensors on the robot allow us to detect these magnets, with which, the bot's location can be projected onto a 2D graph structure (Figure 3.10). As each unique location triggers the hall effect sensor in the same way, the initial position of the bot is entered by the user. After the initial position is noted, further localization is done by dead-reckoning [50]. As shown in Figure 3.10, the magnets form the vertices (V) and the pieces of track connecting the vertices forms the edges (E). This graph structure is built and stored on the controller (smartphone, laptop). As a result, the bot itself does not directly interact with the graph structure, but relies on the controller to navigate the bot. Adding more magnets to a section can increase the localization resolution but this poses a few challenges described in Section 6.3.

The 2D graph structure is traversed by the shortest path using Djikstra's algorithm [51] — $\Theta((|V|+|E|)log|V|))$. As the bot can move in two directions, both up and down, Djikstra's algorithm alone is insufficient to determine the direction

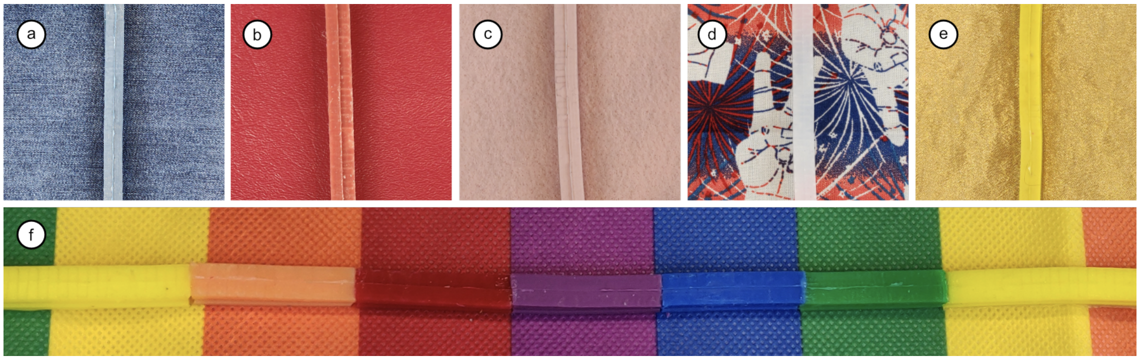

Figure 3.11: a) Blue denim. b) Reddish Brown faux leather. c) Pink felt. d) Multi-colored pattern with a slightly translucent white track. e) Gold satin. As the fabric is extremely shiny, it is hard to blend with the fabric. f) Multiple colors of track epoxied together to form a single striped piece to match the pattern underneath.

in which the bot should move. We solve this by always storing the previous vertex visited by the bot. When a new path is received, a search algorithm is run to determine if the previous vertex is present in the new path. If the previous vertex is present in the new path, the direction of movement is reversed.

3.7 Appearance and Styling

Since our system requires modifications to existing clothes with the add-on track system, it is important to examine the style and appearance of Calico. Here, we selected several common garment materials such as denim, faux leather, felt, satin, thick polyester with stripes of color, and a cloth with assorted patterns — this collection of fabrics presents us with a variety of textures, patterns, and shininess.

For each piece of cloth, we fabricated a 20cm track unit. The tracks were dyed by mixing silicone pigments to match the appearance. Additionally, for the thick polyester with stripes of color, we created small sections of track pieces and glued them together with silicone epoxy. For the cotton with assorted patterns, we fabricated a translucent undyed track with an inlay made using translucent PETG filament. As shown in Figure 3.11, we can successfully match the track's color to most fabrics that come without strong reflections, although for satin, the track can be noticeable under strong lights. The clear track also has limited transparency and may partially block the patterns below.

Chapter 4: Performance Benchmarks

We now present our systematic evaluation of Calico's operational reliability and durability, including speed, payload, climbing capability around corners, slipperiness due to acceleration, and power consumption.

4.1 Speed

The speed of Calico can be influenced by multiple parameters, including the traction and friction between the wheel and the track, slippage, and gravity. Logically, the bot is slower while going up a positive incline and faster going down a negative incline. Adding a payload should also affect the performance.

To test the effect of the meta-material track on the climbing capability at different angles, we built an angular testbed as shown in Figure 4.1b. This testbed allows us to adjust the approach angle in 15° increments across the full 360° range. A piece of track is attached to the testbed with markers of the start and finish line exactly 14cm apart. The speed is calculated by filming the bot at 240fps and counting the number of frames it takes to go from the start line to the finish line. The average readings for 3 trials per angle in 30° increments are recorded in Figure 4.1a.

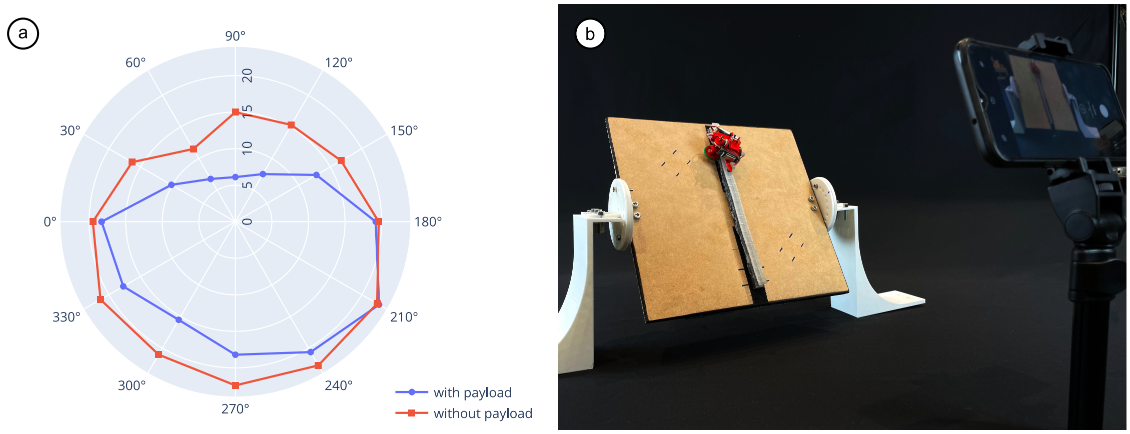

Figure 4.1: a) Speed in cms^{-1} with and without a payload (20gm) plotted against approach angle. b) Test setup used to test the speed with and without a payload.

The track and the weight distribution of the device presents multiple interesting results. For instance, the bot is fastest while going down a negative 120° incline rather than a negative 90° incline. The center gravity of the bot is located away from the track and the body. As a result, while going down a straight drop, the bot flexes the track around the wheel into a shape that increases the contact area and adds additional friction. This flex is absent while going down a negative 120° incline. Similar behavior is seen while going up a positive incline.

As we can see, with the current configuration of the bot, the device moves at 11.5cm/s in the worst-case scenario and 22.7cm/s at best. For instance, if we imagine an application where the bot moves from the wrist to the shoulder with an on-demand microphone required for better audio quality. Such relocation can be achieved in about 4 seconds, assuming that the robot is moving straight up. This speed affords the implementation of real-time interactive applications involving the robot.

4.2 Maximum Payload and Speed under Payload

We also tested each approach angle with increasing payloads. We found that the payload that the device could carry was an extra 20gm across the full 360° approach angle range. Hence, we re-tabulated the speed to examine the effects of the 20gm payload (Figure 4.1a). As expected, the payload only mildly affects the performance of the bot while going down a negative approach angle as the robot is helped by gravity. At worst, the speed is reduced by 60%.

With a 20gm payload, the flexing behavior explained in the previous section is shifted by a few degrees as the payload moves the center of gravity further away from the track. For example, the bot is slowest while going up a 60° incline nonloaded, but with a 20gm payload, a 90 ° incline is the new lower bound of the speed. During the test, we also noticed that inconsistencies with the fabricated track might create hot spots at which the bot sometimes struggles. A few tracks fabricated in an early procedure had air bubbles where the robot would get stuck without flexing the track and going around it. The extra stress added by a payload highlighted these inconsistencies which forced us to reconsider the fabrication procedure. We tuned the shape of the inlay to allow the silicone to settle in more easily without creating any air bubbles.

4.3 Minimum Curvature

As the bot is deployed on the human body, the other main traversal challenge is for the bot to go around curvatures effectively. To ensure the bot can move on all kinds of body terrains, the minimum curvature that the bot can go around has to be satisfactory. This was tested using a custom fixture with a series of printed semicircles installed on top (Figure 4.2). Scenarios such as these prompted the inclusion of the 3D printed inlay. We started the experiment with a 60mm diameter rigid semicircle and continued to reduce it until the bot could no longer go around it. The bot's ability to go around such curves is contingent upon how the wheels flex the track. When the curve becomes too small, the contact area increases to a point where the friction is too high to overcome and flex the track in a convenient direction to allow the robot to move along it.

We found that the minimum diameter that the bot could traverse around for a rigid semicircle was 30mm. Most curves present on the human body are larger than 30mm. As the track is attached to clothing, the bot can further deform the track to go around small curves. Nevertheless, care must be taken to ensure that extremely sharp curves are avoided while designing the track system.

4.4 Slip Due to Acceleration

Previous experiments have shown that Calico can reliably stay on tracks with different orientations and terrains. However, daily activity, such as jumping, sprint-

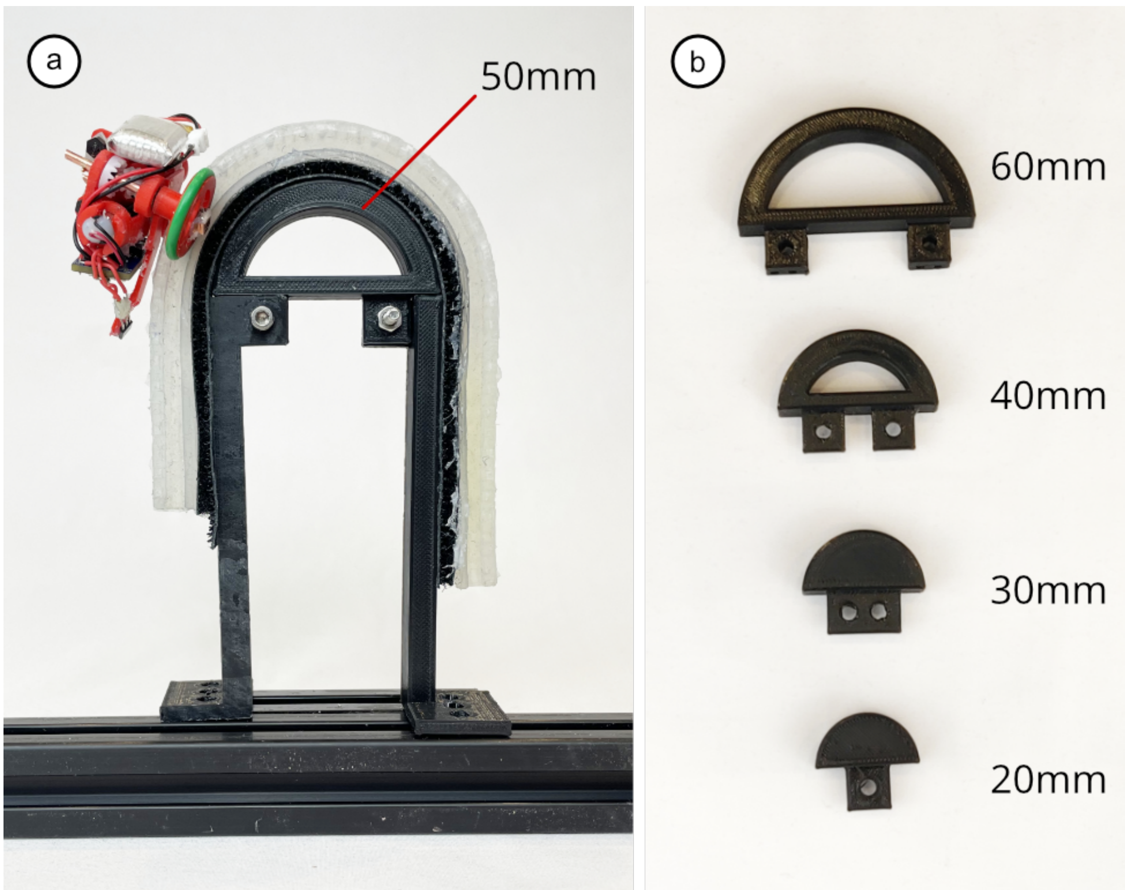

Figure 4.2: a) Test setup to determine the minimum rigid curve that can be traversed by Calico. b) Different curvatures used.

ing, or swinging your arm, may introduce a sudden change of acceleration, creating potential slip. To understand this, we built a test bed that can create controllable angular acceleration (Figure 4.3). A piece of cloth with an attached track is fixed to the test bed. We marked a start position and fixed the bot to that location and then tested the slip at various speeds with g-force automatically logged with the bot's onboard IMU. For each motor speed, we allowed the robot to spin for 5 seconds before noting the slip. Note that for this study, we altered the on-board accelerometer to read at full-scale range (±16g). We calculated the magnitude of the g-force using the Euclidian Norm.

Figure 4.3a shows the results of the experiment. Calico undergoes minimal slip below 15g and starts to slip off completely when the g-force is over 16g. Above 20g (marked in red), Calico tries to go through the 3D printed inlay instead of slipping on the groove.

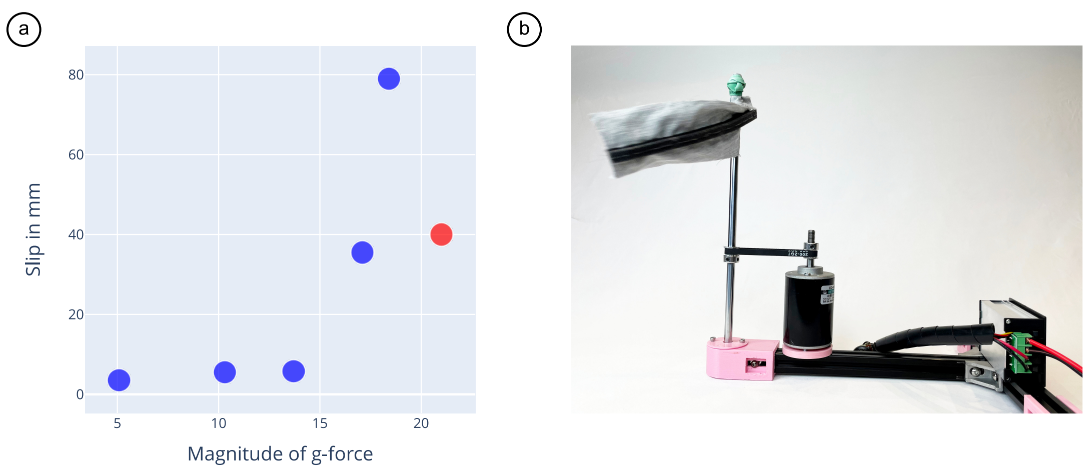

Figure 4.3: Testing the slip of the device when subjected to different g-forces. a) Scatter plot showing the slip vs the g-force encountered. At 21g (marked in red), the wheels broke through the inlay instead of slipping along the groove in the track. b) Test setup used to run the experiment.

4.5 In-the-Wild Testing

Figure 4.4: Testing the resilience of the Calico system under standard user activity.

To further examine the stability and resilience of the Calico system, we developed a testing scenario mimicking everyday activities performed by a user throughout the day. A representative user from the development team performed three activities - walking, climbing stairs, and jogging - for 5 minutes each. The user also jumped a few times at the end of the test. A Calico bot was deployed on the user's clothing and was programmed to travel back and forth between the left wrist and the lower back continuously while he performed the activities. Accelerometer and gyroscope data was plotted in real-time.

Our initial hypothesis expected Calico to miss some magnets due to alignment issues with the hall effect sensor while the user was performing vigorous activities like jogging and running. On the deployed path, there are 16 embedded magnets in total. Throughout the experiment, Calico didn't miss any magnets, thereby accurately moving and staying on the loop. This provides a satisfactory localization accuracy for constant usage even while the user is moving freely.

4.6 Power Consumption

To provide consistent usage without relying on having to charge the device frequently, it's important for the wearable to be energy efficient. The bootloader aids this goal by being entirely event driven — this also reduces the need for additional power saving processes on the application layer. The device's default state is idle ($3\mu A$). At it's peak, when the module is looking for devices to connect to, the micro-controller draws 12mA. During standard usage, processing JavaScript requires 4-8mA.

The two motors consume the most energy (~80mA each during normal movement). The IMU drains $3.11mA$ at worst and idles at $8\mu A$. Other components (motor driver, hall effect sensors) drain less than 1mA. In an extreme case, where the bot continuously travels along the user's body with the IMU reporting readings every 100ms, Calico can have a 30-minute battery life with the 100mA battery we are currently using. When it's idle, Calico can last more than 8 hours. To further expand the operation time, we can include a wireless battery charging module, ensuring full-day usage. The battery capacity can also be increased by designing it to mould to the shape of the wearable.

Chapter 5: Applications

We created five examples, each emphasizing one or more features of the Calico wearable. See the supplementary video for full demonstrations.

5.1 Tele-medicine with Chest Auscultations

Figure 5.1: Calico involves in telemedicine and preforms chest auscultations.

In this example, we showcase the scenario where a doctor can administer the Calico robot for precise chest auscultations remotely. During a televisit, the user can attach a companion stethoscope to the Calico robot but doesn't need to care about the specific location of where to put down the sensor (Figure 5.1). The doctor controls the robot to move along the front chest and stop at particular positions. Because the Calico system has magnetic landmarks, the doctor can monitor the Calico's location with high precision. Once the robot stops at a location, the user pushes the stethoscope against the body for examination. The body signal is sent to the doctor in real-time (Figure 5.1). The scope can also be used to record raw audio at 10ksps which can then be listened to by a doctor.

5.2 Fitness Coach

Figure 5.2: The user receives feedback from a smartphone connected to Calico to correct their plank position. a) Positive feedback b) Negative feedback

One of the challenges for doing exercise is that the movements may not be standard or out-of-shape over time. Since Calico can be relocated to different body areas, it can serve as a personal fitness coach by monitoring the user's movements. Here, we showcase one such mobile app (Figure 5.2). When starting a training session, the user can browse for different movements, for example, plank. Once selected, the Calico bot will move to the user's back — the most effective body location for coaching plank. When the user starts the practice, the Calico will move along the user's back. The IMU readings can tell if the user's back is straight, the key for plank. If the back sags, the bot will notice the user with vibration — generated by quickly moving the bot back and forth at micro-steps. The phone application will also remind the user simultaneously. The user can also switch between exercises with the Calico bot relocate itself with the on-body track system.

5.3 Walkie-Talkie

Figure 5.3: Calico positions itself near the neck of a user to transmit audio.

Calico can be helpful in situations when both of the user's hands are occupied. In this example, we demonstrate that Calico can function as a hands-free walkie-talkie. When summoned, Calico can move from the user's pocket to the left chest. The user can directly talk to others without taking out her phone. The MDBT42Q has a flash storage memory of 512kb and can directly record audio at 10ksps. The on board microphone captures the user's voice in 15 second segments. The length of the audio can be extended by adding a microSD card to the microcontroller. The file can then be downloaded on a smartphone or a laptop. After recording the audio, Calico can retreat into the user's pocket.

5.4 Dance-Dance Companion

Figure 5.4: Performing a dance with the on-body companion. The high speed and climbing reliability of Calico allows us to explore such applications.

In this example, we physicalize a more futuristic concept — Tamagotchi, also known as a personal virtual companion. A 3D printed shell is installed to Calico's chassis, and equipped with fur and a pair of googly eyes, making it looks like a cute small creature (Figure 5.5). The virtual companion can be programmed with different interactions. For example, after the user sits still on a couch for awhile, the companion may come out of the user's pocket, moving around the user's torso,

Figure 5.5: A furry cap is used to make Calico more personable.

seeking the user's attention. The user can interact with the companion with different kinds of taps; the companion moves in various patterns and vibrates to respond.

An additional use case is to have the companion dance with the user. In Figure 5.4, the user is performing an arm wave. When the user raises the shoulder, the companion moves to the shoulder; when the user lowers the elbow, it moves to the elbow; when the user twists the wrist at the end, the companion moves to the end of the track and flashes in red. The user can experience different dance moves in together with the virtual companion.

5.5 Offload from the User

Figure 5.6: Using magnetic connects at the end of the track, Calico can move from one user to another. This functionality can also be extended to other surfaces.

As the final scenario, we explore the concept of offloading Calico from a user's body to the environment or another user. For example, when the user doesn't need the Calico bot at that particular moment, she can connect the end of the track from the sleeve to a wall-mounted key hook. Calico can then move from the user to the wall, to stay among the rest of the user's belongings such as keys. Additionally, a Calico bot can be lent from one user to another. As shown in Figure 5.6, two users can snap the ends of the track on their wrists together using the pre-attached magnetic connectors. The Calico bot can then move across the gap and transfer from the original host to another user. The new user can then connect to the Calico bot using their smartphone. Similar concepts have been discussed for smartphone sharing [52–54] ; we envision that bot sharing can be relevant when the Calico platform matures.

Chapter 6: Discussion and Future Work

We now discuss some limitations and additional considerations for future system design.

6.1 Full-body Auto Calibration for Precise Anatomical Localization

Owing to the landmarks on the track, Calico can localize itself accurately on the track system. However, with Calico's onboard sensing capability, it should be possible to perform anatomical localization, where the bot can figure out its on-body location with respect to the magnets, automatically.

To understand the feasibility of the idea, we ran a proof-of-concept experiment with 5 independent auto calibration trials. For each trial, the user remains stationary in the standing posture with wrists over the stomach forming a 90°angle between the forearm and the bicep. The Calico bot travels through the track along the user's arm while collecting sensor data from the IMU at 15 Hz.

Figure 6.1 illustrates the accelerometer data for one trial with the high frequency noise removed. As can be seen in Figure 6.1, each anatomical location (with grey background) has a unique signal trend. For instance, at the tailbone location, the bot senses positive linear acceleration along the x-axis and a negative value along

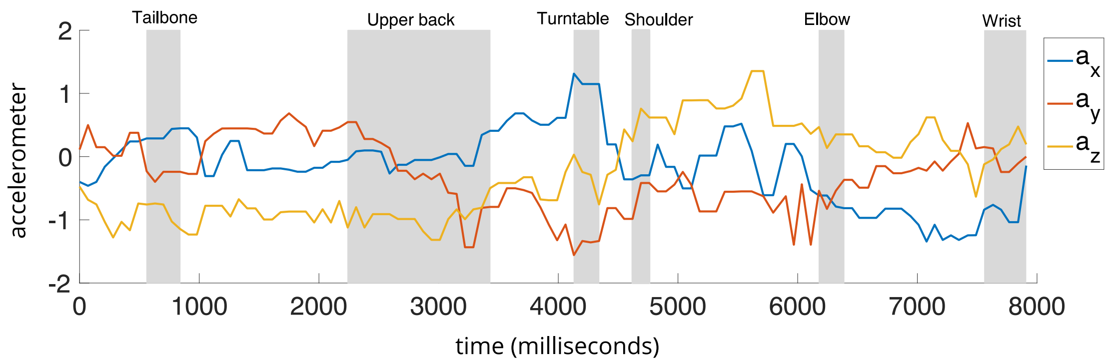

Figure 6.1: The median filtered accelerometer time series data collected during a full body auto calibration step for precise anatomical localization.

the y and z-axis; as the bot moves towards and then reaches the upper back area, the y-axis linear acceleration reaches its maximum and then drops sharply. The negative y-axis acceleration slope is a characteristic signature of upper back, which can be potentially used to identify this location.

To further demonstrate the uniqueness of these trends for anatomical localization, we extract two features: the median filtered 3D accelerometer data and the median filtered 3D accelerometer differentials. We then perform a Principal Component Analysis (PCA) on the 6 features corresponding to six locations (i.e., tailbone, upper back, turntable, shoulder, elbow and wrist).

Figure 6.2 shows a scatter plot of the projected accelerometer data. The data has formed clusters in different areas of the two dimensional space. For example, the data instances at the turntable and shoulder locations form clusters that are fairly different from the rest of the location clusters. While there are partial overlaps among the wrist and elbow clusters, the two clusters can be easily differentiated from the rest.

Overall, the proof of concept experiment clearly demonstrate the potential of

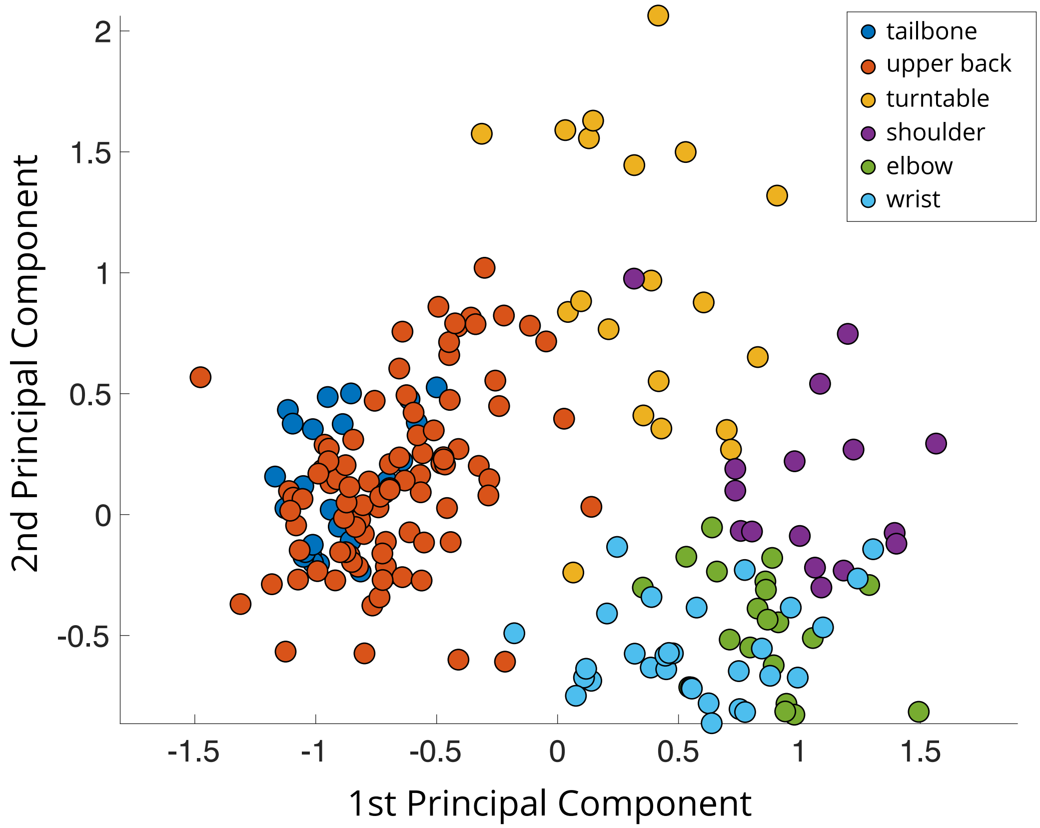

Figure 6.2: shows that anatomical locations form clusters in the two dimensional space of the two principal components.

a full-body auto calibration process for precise anatomical localization. For more rigorous evaluation, comprehensive data collection with a large and diverse cohort of participants is required. Such a large dataset will allow us to develop an end-to-end machine learning algorithm for automatic calibration and localization.

6.2 Track Inflexibility

The current track deployment is only one possible way of laying the track graphs. With a different set of applications in mind, the track topology can vary. However, in the current design, the tracks are not changeable once they are attached to the garment. Although different pieces of clothing could be used based on the context, the inflexibility may be undesirable.

One way to improve this is to make tracks removable, which can be done by adding snap buttons to the bottom of the track units and also as common junctions to the clothes. Based on the applications, the user can install the tracks among these junctions to create a custom on-body track network. However, identifying the most applicable junction locations will require future research.

Although it is possible to design a track layout that includes all the major points of interest, not all points of interest are going to be commonly used. Reducing the complexity of the track system would allow the bot to travel faster between points of interest. In the current design, once a track system is attached to a certain piece of clothing, the points of interest can't be changed for that particular piece of clothing. Although it can be argued that different pieces of clothing can be used based on the context, the inflexibility might be undesirable. Additional work can be done to increase the ease of installing and reinstalling the track system on the body.

6.3 Localization Resolution

Additionally, different methods can be designed to localize the robot on the track system. Assuming a minimal slip between the wheels and the track, adding an encoder to the motor assembly would allow us to detect and compensate for the slip.

During our testing we realized that the localization resolution is only limited by the minimum distance between the magnets. The hall effect sensor was able to detect multiple magnets even when the cylindrical magnets were placed 1mm apart. This would provide us with an approximate localization resolution of 4mm, not accounting for the errors due to momentum. But, when a track is produced with magnets only 1mm apart, the flexibility of the track is largely affected. As the number of magnets increase, the live-hinge pattern is reduced. This leads to very low flexibility, thereby making the track impractical to attach on clothing.

The live-hinge inlay can also be completely replaced with a flexible magnetic tape which makes the use of alternating poles that can be detected by the hall effect sensor. This reduces the fabrication complexity as the tediousness of implanting magnets will be replaced by allowing the silicone to cure around the magnetic tape. Although this reduces the fabrication complexity, the flexibility issue still remains. Designing methods to fabricate a flexible inlay with alternating magnetic poles could alleviate this issue. Additionally, different methods can be designed to localize the robot on the track system. Assuming that there is minimal slip between the wheels and the track, adding a magnetic encoder to the motor assembly would allow us to know the exact distance that the robot has travelled. A hybrid mechanism that combines data from the IMU and the duration of the voltage applied to the motors and then runs it through a pre-trained neural network could also provide distance figures.

6.4 Limitations Due to BLE

To maintain a small footprint and low energy usage, we used a BLE enabled microcontroller. Due to the 20 byte MTU configuration, streaming live data is limited. As a result, using sensors at high sampling rates would pose a challenge. Some of these issues can be alleviated by adding a microSD card connected over SPI. A dedicated Bluetooth EDR radio along with a battery that fits the device's form factor could also be used. Bluetooth A2DP would also be a welcome addition. In this case, additional work needs to be done to maintain low power consumption. For instance, while performing chest auscultations, recording long pieces of audio might be beneficial for medical professionals.

6.5 Long Term Perception

Earlier work [48] has tested the perception of an on-body mouse-like wearable that moves along a user's arm. Although this system was bulky and limited, it provides a small window into how a system like this may be perceived. In this paper, we have directed a lot of effort into limiting the size of the device and providing aesthetic flexibility in the hope of improving social acceptance. In the future, we plan on deploying Calico system on users to study the long term user perception.

6.6 Intrusive switching mechanism

During our testing, although we weren't physically hindered by the turntable or the system itself, we noticed that we tended to move with care in order to not damage the turntable. We have demonstrated that a turntable system can be used to switch tracks, but the design is still obtrusive and slightly bulky. For more practical applications, it might be prudent to design the track system in a way that reduces the number of coinciding paths. Further work can be done to identify better ways to switch tracks or to avoid track switching altogether. If the footprint of the track can be reduced to an extent where multiple parallel tracks along the same path doesn't make the system bulky, an implementation without any track switching might be feasible.

6.7 Exposed magnets

Sensing landmarks and switching between tracks all require precise physical location data. Hence, we use a large amount of magnets all over the system to make this happen. Although the magnets are really small and the magnetic field doesn't interfere with daily life, at times the magnetic field affects the sensors on the device. The magnetometer provides unreliable data due to the on-board motors and the large number of magnets in the system. The large number of magnets might also create awkward situations where strange items get stuck to the user's body. This problem can be overcome by developing a precise localization mechanism that only relies on the components present on the robot. For example, a visual encoder along with a striped wheel can be used to detect the distance travelled by the robot. As the robot experiences minimal slip, the travelled distance can be calculated precisely.

Chapter 7: Ethical Considerations

As technologists, it is remarkably easy to focus on the novelty of the idea and the system implementation while disregarding the user's deep underlying motivations. Fit4Life [55] explores this idea by employing the use of a satirical system designed to help a user lose weight. Along the way, the system loses sight of the user's goals, and the data tracking mechanisms start to invade the privacy and the will of the user massively. As Calico is to explore the concept of on-body wearables, it is important to think about the ethical implications of tracking personal data and stay aligned with the user's goals while maintaining user privacy. For example, tracking the posture of a user can be beneficial for their long-term health; using the same data to motivate the user physical attractiveness is no longer aligned with the goals of the individual, and may affect the mindset of the user in the long term.

Extra care must be taken while implementing applications that involve personal companions. The effect of a digital companion on the user's long term mental health must be thoroughly considered. Jaron Lanier's work [56] explores the evolution of personhood based on how computation is perceived. Extending the presence of computation to an always-on device on your body with the capability to move around it based on the context has a chance of strongly influencing the user's perception. Whether the influence has positive or negative connotations must be explored thoroughly.

It's also easy to imagine a world where a Calico-like system can be deployed to track data in order to extensively monitor people. A relocatable wearable deployed on a human even with a few sensors can provide a treasure trove of information that can be abused by corporations that can monetize the data collected by the device. Keeping the goals of the user in mind while deploying such systems is extremely imperative.

In addition, this treasure trove of data also creates questions about data privacy. Creating protocols and mechanisms that allow users to maintain control over their data and ensures user consent at all times while collecting data is a mammoth task that has to be handled effectively before considering the large scale deployment of a relocatable wearable. Deploying such systems in a hurry based on their novelty without adequately considering the ethical implications can be catastrophic.

Chapter 8: Conclusion

We presented Calico, an interactive relocatable wearable using on-cloth track systems. We reported the system design consideration, the implementation detail, and system evaluation. As Calico enables fast, reliable, and precise on-cloth locomotion, we highlighted such capability with a suite of applications.

Although further work is required to extend the deployment of Calico into a long-term daily life scenario, we believe that relocatable wearables on a track system is a promising area of wearable research.

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