

Rovables: Miniature On-Body Robots as Mobile Wearables

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ABSTRACT

We introduce Rovables, a miniature robot that can move freely on unmodified clothing. The robots are held in place by magnetic wheels, and can climb vertically. The robots are untethered and have an onboard battery, microcontroller, and wireless communications. They also contain a low-power localization system that uses wheel encoders and IMU, allowing Rovables to perform limited autonomous navigation on the body. In the technical evaluations, we found that Rovables can operate continuously for 45 minutes and can carry up to 1.5N. We propose an interaction space for mobile on-body devices spanning sensing, actuation, and interfaces, and develop application scenarios in that space. Our applications include on-body sensing, modular displays, tactile feedback and interactive clothing and jewelry.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous.

Author Keywords

On-body robotics, mobile wearable technology

INTRODUCTION

What if wearable devices could move around the body? For example, fingernail-sized robots that could seamlessly assemble into a wristwatch or a nametag. Current wearable technologies are immobile devices that are worn on the body, such as smart watches (e.g. Pebble, Apple Watch), head-mounted displays (e.g. Google Glass), and fitness trackers (e.g. FitBit). As technology becomes smaller and more power efficient, it will move closer to the body. Even now we are witnessing the appearance of sensor-enabled fabrics [19], and implanted [9] or on-skin electronics [25, 11]. However, this future does not accommodate the possibility of dynamic devices. We envision

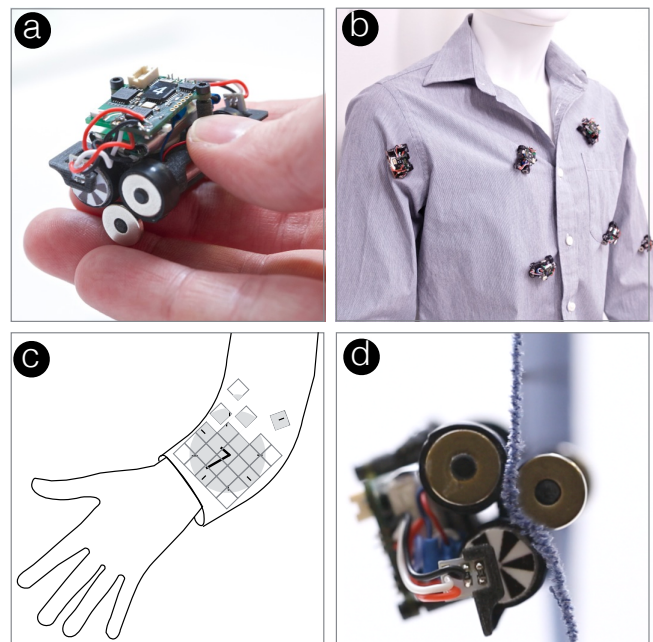


Figure 1. a) Current Rovables prototype. Magnetic wheels provide an ability to climb vertical clothing. The onboard electronics and sensors provide autonomous operation. b) Multiple Rovables climbing a shirt. c) In the future, Rovables could become fingernail sized. A swarm of them can create an on-body interface or do distributed sensing. d) Rovable climbing a vertical piece of fabric.

that future wearable technology will move around the human body, and will react to its host and the environment.

Most organisms from bacteria to trees (mobile seeds) have ways of locomotion, as finding a right location is crucial to their survival. Although computationally powerful, most wearable technologies do not have such abilities. Lack of locomotion severely limits the abilities of on-body devices. With locomotion, wearable devices can become truly *autonomous*; they can perform self-maintenance, such as finding a port for charging the battery. Locomotion can enable *spatially-aware sensing*. The location of the sensor is often central to its performance, and sensors will be able to find the optimal location on their own. For example, for accurate heart rate monitoring, sensors need to be placed at the right locations around the

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UIST'16, October 16–October 19, 2016, Tokyo, Japan.

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DOI: <http://dx.doi.org/10.1145/2984511.2984531>

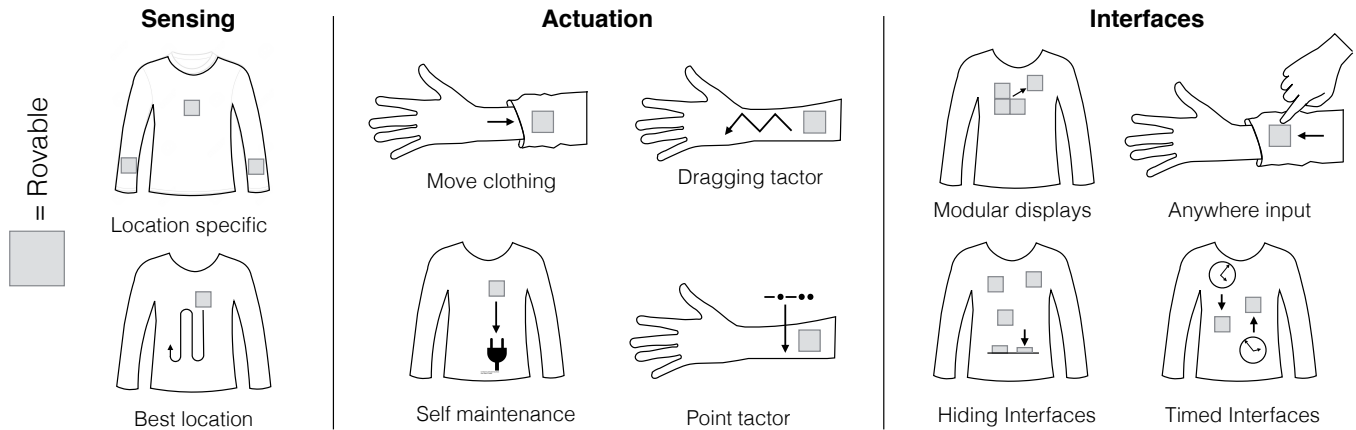


Figure 2. Example interactions using Rovables. Gray squares represent one robot.

heart. Furthermore, such wearable devices will have the ability to *actuate* their environment, such as moving something out of the way. Lastly, such devices will be able to appear and disappear seamlessly. This idea fits the vision of ubiquitous computing [26], in which profound technologies disappear into the background.

In this paper, we start exploring the future where wearable devices are dynamic and can move around the body. To realize this concept we developed two core technologies. First, the magnet-based locomotion system, which allows the device to move freely on clothing. Second, a navigation and control system that allows the device to track its course and position. We believe in the future Rovables can become the size of the fingernail and completely autonomous. We are already witnessing impressive advances in microrobotics such as the Robobee [28], a miniature flying robot.

The contributions of the paper are as follows:

1. New paradigm of mobile on-body devices, and their possible interactions space.
2. We implemented a novel platform, composed of miniature robots that can move on unmodified clothing. The robots are held in place by neodymium magnet wheels gripping between the fabric. The robots are untethered with onboard power, computation, and wireless communications.
3. We developed algorithms and sensors to track and control the position of each robot, that allow limited autonomous operation.
4. We performed technical evaluation such as payload weight, battery life, and localization accuracy.
5. We explore a range of application scenarios such as tactile feedback, body motion sensing, mobile jewelry, and wearable displays.

INTERACTION SPACE

In this section, we will describe the design space and interaction potential of Rovables. Unique interactions can be achieved with the ability to move and act on the environment,

and to sense location on the body. We see three important categories: actuation, sensing, and user interfaces. Although we provide distinct categories, they are not clear-cut and can be mixed together. Use cases from each category are provided in the applications section.

Actuation

Tactile Display. Rovables can be used as a versatile tactile display. The robots can be equipped with a vibration motor or a linear actuator that pokes the skin. The feedback can be provided in two ways. First, the robot can move to a specific location and provide tactile feedback. Second, the robot can provide tactile feedback by dragging the factor across the skin. Skin drag effect has been shown to produce stronger feedback than only vibrations [10]

Actuating clothing. Rovables can act on external objects such as clothing. The robots can attach themselves to clothing with hooks, and push/pull pieces of clothing. As a result, clothing can be self-adaptable for both practical and aesthetic reasons.

Self-maintenance. The robots can perform self-maintenance. If their battery is running low, Rovables can locate a charger. If the robots malfunction, they can detach themselves from the host, when they sense a repair station.

Sensing

Rovables can provide an extension of Body Area Networks (BAN), a term describing wireless sensor nodes attached to a body to perform continuous health monitoring [14]. Many types of sensors require being in a specific location. With a large number of sensors, it is cumbersome to place individual sensors in the right location. For example, to perform whole body motion tracking with IMUs, 17 sensors have to be manually positioned in a specific orientation on the body. Mobile sensors can automatically position themselves in the right locations. Also, often it is not known in advance where the best location is. Rovables can obtain data in multiple locations, and find the best one.

User interfaces

Rovables can function as a physically-reconfigurable user interface. Robots can move to a location to provide both input

and output functionality on demand. Each robot can carry a display on the top, together creating a *modular display*. The robots can assemble together to create a larger display or to change its form factor. Such display can adapt based on the circumstances. Besides output, the robots can be used for *always-available* input, such as touch-screen and gesture sensing. Such input capabilities are now autonomously mobile and can go where they are needed.

The robots can *hide* and get out of the way if they are not needed. For example by moving into a hidden pocket inside a jacket or by detaching from the body. Also, they can hide by serving a decorative function, such as jewelry. Also, Rovables can be *timed interfaces*. In other words, programmed to have a routine and take different roles throughout the day. For example, sensing in the morning and display in the evening. This allows robots to move very slowly, so their movements are not perceptible for the host.

Example interactions throughout the day

To better understand how the different interactions fit together, we provide example interactions throughout a day of an imaginary adult, Mary. Here we assume that Mary wears tens of fingernail-sized autonomous robots.

In the morning Mary goes to the gym. Rovables move to her limbs, to track all of her movements, and to the chest to measure respiration and heart rate. This allows collection of extensive data for analysis and feedback. Next, Mary takes the subway to work. To watch a movie, the robots assemble on her arm to create a display. This eliminates the need to have other devices, such as smartphones. If it gets too hot the robots will move Mary's sleeves up. Once Mary gets to the office, the robots assemble into a name tag on her chest. Robots will gently tap Mary on the shoulder if she gets an important email. After work, Mary goes to a restaurant with friends. The robots will form a decorative necklace and a matching bracelet. After the restaurant, Mary decides to bicycle home after dark. For safety reasons, robots move to her back to make red stop lights, and to the front to illuminate the path. They will also tap Mary on left or right shoulders to indicate GPS directions. Once she goes to sleep the robots will monitor the quality of her sleep and wake her up at the best moment. Throughout the day, the robots will collect extensive physiological data to learn habits and for health diagnostics.

DESIGN CONSIDERATIONS

At the core, the robot should be unobtrusive to the wearer. To achieve that, we consider the following design criteria to be important:

1. **Small form-factor.** The devices should be as small and as lightweight as possible. Since the device is close to the body, smaller size and weight is less obtrusive for the human host. Furthermore, clothing has limited space for travel, especially places such as sleeves. The size should be limited to 1.5cm x 1.5cm, the diameter of a small wristwatch.
2. **Navigation** The robot should be able to track its positions on unmodified clothing. Such a system should not require external aids, such as cameras. This will allow autonomous

movement on the host's clothing, without disturbing or limiting the wearer.

3. **Mobility** The device should move freely vertically on unmodified clothing. Furthermore, it should be able to move on loose and wrinkled clothing. The device should be able to carry a payload, allowing it to actuate clothing or to carry sensors.
4. **Communications** The device's basic functionality should include wireless communications with external devices. This will allow coordination between multiple robots and interaction with devices such as PCs and mobile phones. Communications between robots will enable more complex behavior and tasks.
5. **Power** As manually charging multiple robots can be time-consuming, the robot should have an ability to charge itself. Also, the robot's battery should last for at least 30 minutes of movement, and for 8 hours without movement. This will provide enough time for the robot to perform any of the tasks that were proposed in the interaction space, and return to the charger.
6. **Platform** The system should be designed as a platform, so anybody can build and experiment with wearable robots. The system should be inexpensive to build, modular, and flexible enough to easily add more components and interfaces.

PREVIOUS WORK

On-body robotics is a largely unexplored area. Though vertical climbing robots have been demonstrated in the robotics field, they are often limited to specific materials, and they have not spread into other fields such as Human-Computer Interaction, due to specialized technologies. However, the availability of low-power electronics and miniature gear motors enables broader explorations. We are not aware of any work that explored free-moving on-body robots beyond movement mechanisms. Previous work can be categorized into three fields: First, climbing robots from the robotics field. Second, actuated interfaces and invisible interfaces in human-computer interaction. Third, transforming clothing in fashion.

Climbing robots

The idea of vertical climbing has been explored in robotics. For example, Stickybot [12] mimics gecko by using adhesive feet to climb vertical surfaces. Similarly, Waalbot [16] uses adhesive rotary legs to climb vertical surfaces. Rubbot [2] and Clothbot [15] uses two wheels to grip into folds on clothing. CLASH [1] robot has six legs which can penetrate into cloth to enable vertical adhesion. Although the work in robotics demonstrates the possibility of vertical climbing, it does not explore applications. Also, the robots are not miniaturized enough to explore on-body applications.

Actuation in Human-Computer Interaction

A few works in Human-Computer Interaction (HCI) explored on-body robotics for various applications. The concept of Parasitic Mobility [13] illustrates sensor nodes that can jump from one human host to another. Perhaps, the most closely

related work developed a mouse-like robot that moves on a rail mounted on the arm [23]. In this early work, authors do a limited user study to explore how the participants feel about the robot. The prototype is limited as it is bulky and can only move on a specially-designed rail. One intriguing concept [3] showed a quad-copter that can attach to the wrist, fly around to take pictures, and come back.

A lot of work in HCI focuses on adding actuation to objects and devices. For example, Pigmy [18] is a ring with moving eyes and mouth, used for storytelling applications. One work developed a shape-changing mobile phone [7]. Other works demonstrated an approach for making shape-changing devices using pneumatic actuation [5, 29], an array of servo motors [17] or shape-memory alloys [20]. In contrast, we are more concerned with mobility and creating interfaces on demand.

Invisible Interaction in Human-Computer Interactions

Researchers in HCI have explored the concept of invisible or re-configurable on-body interfaces that users can interact with. The work of Harrison [8] explored using projection to create graphical touch-based interaction on the body. Others have explored using discrete or embedded sensing to sense gestures across the body for "invisible" interfaces [21]. These systems cannot provide tactile feedback and rely on a projection which may not work in all lighting conditions, or focus only on input.

Robotics in clothing and fashion

The fashion industry has been captivated by the idea of clothing that can automatically adapt based on the environment. ZipperBot [27] is a motorized zipper that can automatically zip and unzip. In 2006 a fashion show featured clothing that transform by using motors and pulleys [22]. The work in this area is mostly task specific and does not conceptualize a generalized platform.

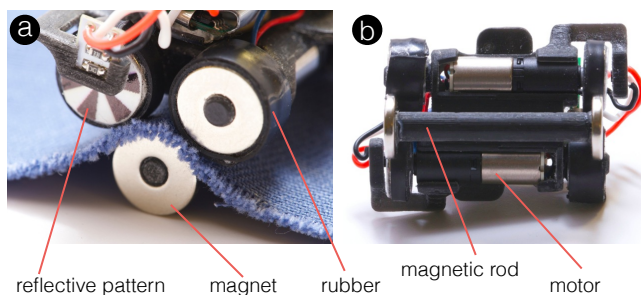


Figure 3. Illustration of the magnetic drive system. a) The fabric is held between the top two wheels and magnetic rod on the other side. All the wheels are circular neodymium magnets. The reflective pattern on the wheels is used for the infrared encoder. b) Underside view of the chassis, with the fabric, removed. Two motors are visible in this view.

IMPLEMENTATION

In this section, we will describe the mechanical and electrical design of Rovables. All the design files will be open sourced at github.com/rovables

Vertical-climbing magnetic drive

The magnetic-drive chassis is shown in Figure 3. We used two 136:1 planetary gear motors (TGPP06-D-136, TT Motor) for

movement. Such motors are only 6mm in diameter and have high gear ratio. The gear motors were attached to neodymium magnet wheels (9mm diameter). Next to the drive wheels, another set of neodymium magnet wheels was used to stabilize the movement. Those wheels were connected by miniature ball bearings (4mm diameter), to reduce friction. Both sets of wheels were covered with 1mm-thick Neoprene rubber tires to reduce slippage. On the other side of the fabric, a rod with two neodymium wheels locked into the upper wheels. Because of magnetic attraction, the magnetic rod is moved with the upper wheels. This holds the robot in place, regardless of its orientation. The body of the robot was 3D printed in one piece using Objet Eden260VS (Stratasys)

Other works used different mechanisms for climbing, such as by pinching the fabric [15]. Although our approach requires a magnet on the back side, we picked it for simplicity and for ease of miniaturization.

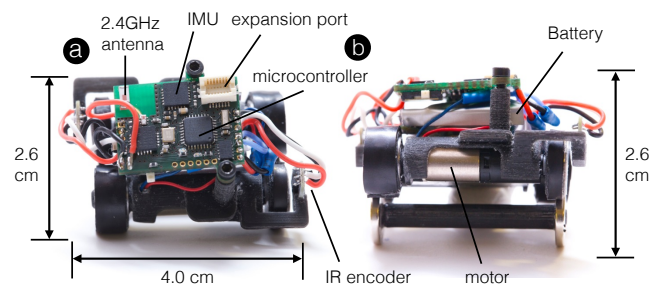


Figure 4. Picture of the electronics and sensors. a) Top view. Custom designed circuit board is visible on the top. Infrared encoders are placed on left and right wheels. The expansion port on the top is used to add more functionality. b) Side view. As visible in this view, the battery is sandwiched between the motors and the circuit board.

Hardware

The system diagram is shown in Figure 6. To reduce the size and weight we made a custom 1mm-thick PCB (printed circuit board), as shown in Figure 4. We added a 14-pin connector so shields can be added for more functionality (e.g. additional sensors). We exploit this feature in the applications section. The main processor is ATmega328p (Atmel). The system is powered by 100 mAh lithium polymer battery.

For radio communications with the base-station we used 2.4GHz radio; nRF24L01+ (Nordic Semiconductors). We decided to use a custom wireless protocol versus standard (Bluetooth, WiFi) to allow control of multiple robots without large latency while reducing power consumption. Furthermore, 2.4GHz frequency allowed for a miniaturized antenna. The base-station contained the same nRF24L01+ radio with extended range antenna. It also contained ATmega32u4 (Atmel) microcontroller to communicate to PC over USB, and to control the radio. We used a server-client architecture for communications. On the PC side, C++ based openFrameworks was used to control Rovables, process and visualize data. In this configuration, the base-station is the server, and the robots are the clients. The robots send the data to the server at 10Hz intervals. To prevent data collisions with multiple radios the retry period was randomized for each robot.

For orientation sensing, we used an MPU6050 (InvenSense) inertial measurement unit (IMU). It contains 3-axis gyroscope and 3-axis accelerometer, and can calculate 3-D orientation on-board. To estimate the traveled distance and the speed, we designed incremental infrared optical encoders with GP2S60A (Sharp). The encoders work by measuring the changes in infrared reflectance of a disk with alternative white and black stripes. The disk was printed on glossy poster paper and glued on the wheels. To generate digital interrupts, the encoders were connected through a Schmidt trigger. We didn't use magnetic encoders because of interference from magnetic wheels. For IR proximity sensing four TSSP77P38 (Vishay) were used. The sensors were mounted on the removable display shield, which is further described in the applications section and Figure 11.

Wireless Charging

By putting an inductive coil (WR221230-36M8-G, TDK) on the undercarriage, Rovables can charge wirelessly. The coil is shown in Figure 5. The coil is only 0.5 mm thick, so it does not interfere with movements. The charging was done using 13.56 MHz Qi wireless power standard. As a secondary purpose, the charger can serve as home, for the dead-reckoning system, described in the next section. When the device goes home it can re-calibrate to reset the accumulated error.

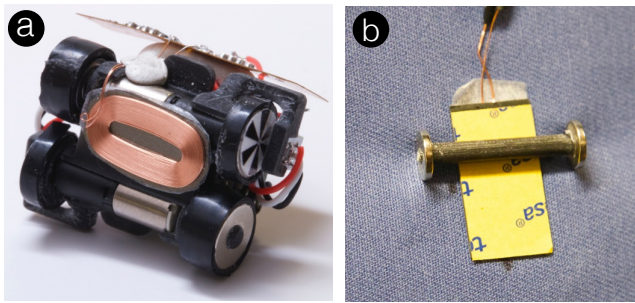


Figure 5. The wireless charging system. a) The receiver coil is mounted on the underside of the chassis. b) The yellow transmitter coil can be taped on the back side of the fabric. The Rovable is parked on the coil, as seen by its magnetic rod. The main body is on the other side of the fabric.

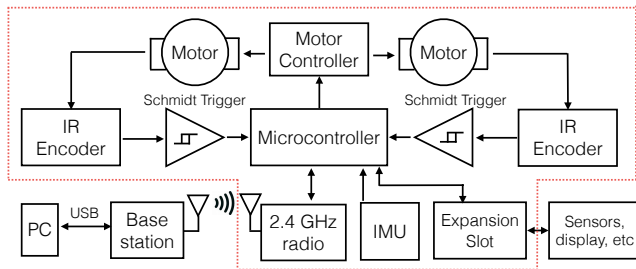


Figure 6. System diagram. The parts inside the red dashed lines are on the main board.

AUTONOMOUS NAVIGATION

Rovables need to have the ability for autonomous navigation. Accurate autonomous 3D navigation of robots on complex surfaces is still an open question in robotics [4], and our efforts

provide an initial exploration. In this section, we discuss how we implemented the limited autonomous operation, and how it should work ideally.

Localization

For Rovables to move autonomously around clothing, their position has to be tracked. Localization is difficult for the following reasons. First, fabric and cloth have complex and uneven 3D shapes. Second, the localization system has to fit inside the small robot and use little energy. Third, it should be self-contained, without big external components (e.g., cameras) or wires, and work on unmodified clothing. These challenges exclude off-the-shelf tracking systems, such as magnetic tracking (e.g., Polhemus) and infrared camera tracking (e.g., OptiTrack) systems. Localization with Bluetooth [24] or other radio signals appear more attractive as they can be integrated into the base station. Unfortunately, they have limited accuracy (12.5cm wavelength for 2.4GHz) and high power consumption.

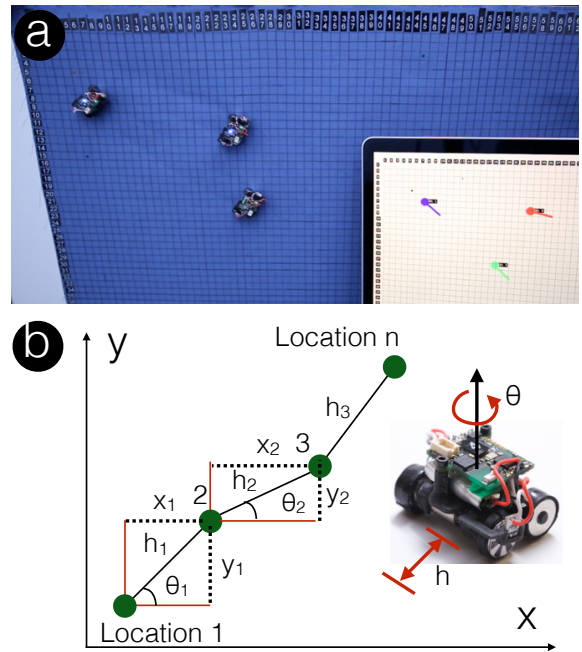


Figure 7. Localization system. a) Localization of three Rovables simultaneously. The square pattern on the fabric was not used for actual localization, but to provide visual aid during for the developers. b) The graphical representation of the dead-reckoning algorithm. The location is determined by previous location, yaw angle, and the traveled distance.

We used dead-reckoning for localization. Dead-reckoning is a position estimation algorithm, where current location is determined from the previous position. Our system uses three sensors: encoders on both motors allow distance and angle data, IMU provides relative orientation, and IR beacon provides a starting reference point for dead-reckoning. With four IR proximity sensors on the robot, the IR beacon could be localized, even with a large dead-reckoning drift. We could not use a magnetometer, because of interference from magnetic wheels. Our current implementation works in planar surfaces, but not accurately in full 3D. With more memory and

computational power, we believe our approach will work on any complex clothing.

The dead-reckoning algorithm works as following. θ_n is the yaw angle. The distance traveled is h . The scaling factor q was used for conversion of encoder data onto centimeters.

$$x_n = x_{n-1} + qh \cos(\theta_n) \quad (1)$$

$$y_n = y_{n-1} + qh \sin(\theta_n) \quad (2)$$

Path planning

The computer (server) does not control the movement of the robots directly. It transmits the commands for the robots to accomplish. This is because the radio communication can be faulty and unpredictable. The server also keeps tracks of the overall map and where robots are in relation to each other.

There are three basic commands: (1) move specified distance forward, (2) move specified distance backward and (3) turn to a specific angle. Using these three movements a complex path can be followed. Each of the three movements was executed with different PID (proportional-integral-derivative) controllers. Without the PID controller, the robot would not follow a straight path, as the fabric surface is not even, and motors are not symmetrical. The IMU yaw angle was used to correct the course. Also, yaw angle was used to control turning.

As shown in Figure 7, we made a fabric test-bed and corresponding software for testing the path planning and navigation. The test-bed was mounted vertically, to reflect actual usage.

Fully autonomous operation

In this section, we will describe how the autonomous system should ideally function. A mobile phone or another wireless device can act as a server and base station for Rovables. The user would scan the garment's barcode to find and load the 3D model of the garment into the server. The 3D model is necessary for localization. Next, the user would attach a base station to the backside of the fabric. The base station has two purposes: charging and dead-reckoning starting point. This can be as simple as putting a smartphone into a pocket. Many phones have inductive coils and thus can serve as a charging base station. Lastly, a small IR beacon would be pinned on top of the base station. This will allow the robots to easily find the starting point and the charger. Finally, the robots would be placed on the clothing. They can be placed anywhere, as they can automatically find the IR beacon. Throughout the day robots will need to go back to the base station, to recharge and reset dead-reckoning errors. No intervention from the user would be required. The robots would only move when the user is not moving. This can be easily detected by IMUs. During body movements the clothing can have unpredictable deformation, thus confusing the navigation system.

TECHNICAL CONSIDERATIONS

Payloads and forces

It is important to quantify the force that Rovable can pull and how it is influenced by the type of fabric. This determines how

much extra weight it can carry, which enables interactions such as actuating clothing.

The force of attraction between wheels and the magnetic rod mostly depends on the thickness of clothing, as shown in Figure 8 (top). The measurements indicate the minimum force needed to pull wheels and magnet rod apart. Generally, thicker clothing has lower attraction forces. The maximum force is 4.2N when there is no clothing in between. Measurements were done with Series 5 force gauge (Mark-10).

Given a certain power supply, the climbing force of Rovable depends both on the thickness and fabric of clothing. The thickness is dominant but for some materials like linen, the climbing force does not follow the trend because of low friction coefficient. Figure 8 (bottom) reflects the force with the motor running at 3.7V DC on a horizontal plane. Its payload when going vertically will be the measured force minus its own weight, which is 0.2N.

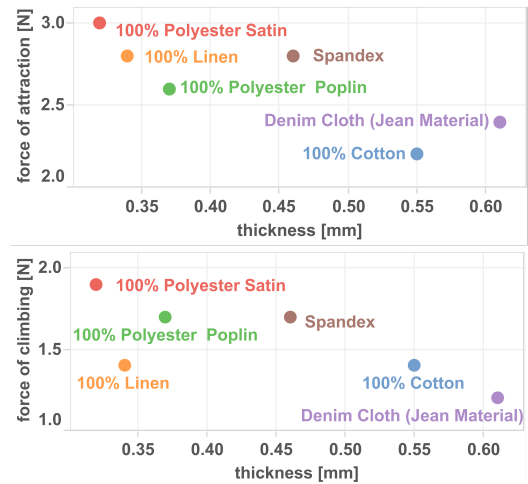


Figure 8. Measurement of attraction (top) and climbing forces (bottom) on different fabrics.

Power consumption and battery life

The maximum power consumption is 120.4mA (398mW), which allows for a battery life of 45 minutes with a 100mAh battery. This is the power required with motors on and all systems on (IMU, wireless, encoders). Motors use the most energy: 91.9mA. The encoder's infrared LEDs consume 20mA. The rest of the electronics consume just under 8.5mA.

Assuming that all systems will not be active all the time, the battery life could be greatly extended. For example, the optical encoders can be disabled when motors are not running. The device can wirelessly stream data for 11.8 hours if the motors and encoders are off.

Wireless communications

Each Rovable transmits and requests a 32-byte packet every 100ms, providing a data rate of 0.32Kb/sec. The network supports up to 3 robots reliably. With more robots, data collisions become more frequent and cause errors and large latency. In the future, collisions can be avoided with synchronization and by allocating transmissions into slots.

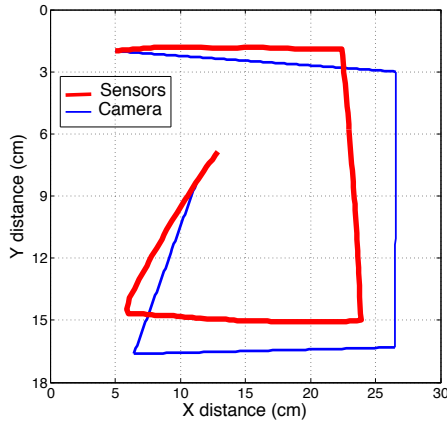


Figure 9. Localization accuracy on a 2D fabric. Comparison of a camera (ground truth) and on-board sensors for localization of one path.

Localization accuracy

As shown in Figure 9, we tested localization accuracy using onboard sensors and a reference camera. The path was recorded on a calibration fabric, which is shown in Figure 7. The robot's movement from the camera was manually analyzed and was assumed to be the ground truth. We found that our localization algorithm has a mean error of 1.95cm and a standard deviation of 1.03 cm. As Figure 9 shows there is an error in both linear distance (encoders) and yaw angle (IMU). The possible sources of error include limited resolution of the encoder (2.4mm) and wheel slippage. Furthermore, the IMU had a yaw angle error of about 6.4 degrees, as measured with reference angles as the ground truth. The IMU did not experience drift, as on-chip algorithms corrected for it.

The accuracy can be improved by using Kalman filter, which is commonly employed in robotic localization. Kalman filter combines the data from multiple sensors (encoders, IMU, motor commands) to provide a better location estimate. Our current system does not have enough memory to run Kalman filter in real-time.

APPLICATIONS

In this section, we will introduce the potential applications of mobile on-body interfaces. The applications were created to explore the design space, as proposed in the interaction space section and Figure 2.

Body motion tracking

Core interactions: *Location-specific sensing*. Motion capture is used to record the movement of people or objects. Motion capture has many applications such as in medicine, sports, and gaming. Most of the current systems use optical tracking, which has limited use, as it requires setting up cameras around the object. Although inertial motion capture systems use on-body sensors, they require a long process of placement and calibration of IMUs on each joint of the body (as many as 17 sensors). Rovables can become a motion capture system, by using their IMUs. The process can be automated, as Rovables can travel to each joint and calibrate themselves.

We developed a kinematic chain model of the human body using openFrameworks library [6]. The data from IMUs was fed into inverse kinematics equations to track the positions of the joints.

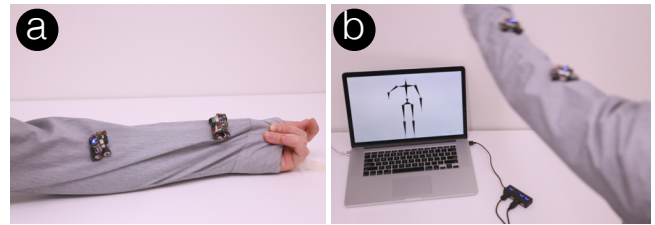


Figure 10. Using Rovables for motion capture. a) Rovables move to the right position on the arm. b) The kinematics of the arm is reconstructed on the screen. With more Rovables whole body skeleton can be reconstructed.

Wearable displays

Core interactions: *Modular displays*. We designed a display shield that connects to the expansion port on Rovables, as seen in Figure 11. The shield adds a capacitive touch display with 63 RGB LEDs (Neopixel Mini). Also, it has an ATSAM21G (Atmel) microcontroller, which allows playing and storing animations. On each side, the shield has IR LEDs and IR proximity sensors, so it can precisely connect with another LED shield or follow an IR beacon. To make it easier to link and align with another shield, each side has two magnets. The display allows us to develop and test scenarios and algorithms where Rovables cooperate to make a larger display.

We developed a scenario where displays can become various output accessories. As an example, we developed an application scenario where one display-enabled robot is on a wrist and displays analog watch. When the user goes into a social scenario, the robot moves to the chest and links up with another robot to form a name tag, as a larger display. When the user goes for a bicycle ride, the displays move to the back to form as safety turn lights.

Moving Fabric

Core interactions: *Actuating clothing*. By attaching the robots to clothing, they can serve beyond individual roaming elements and expand to alter the shape of clothing through movement. With the addition of a small Velcro hook on the robot casing, the robot attaches itself to the ends of a shawl which shape-changes into a scarf according to context, such as temperature change.

Interactive Moving Jewelry

Core interactions: *Hiding interfaces, timed interfaces*. With an aesthetic cover, the robot is transformed from a machine to a piece of jewelry, opening the space for decorative and functionally synthesized applications on the body. We present the example where the Rovable doubles as a brooch and microphone/speaker. It normally serves as a decorative brooch, yet when the wearer receives a phone call, it shifts close to the neck to serve as a microphone/speaker in the case when the wearer's hands are full.

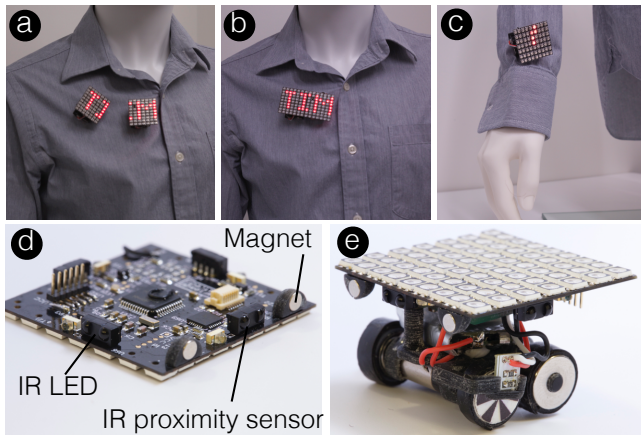


Figure 11. Wearable displays application. a) and b) The displays link together with magnets to form a larger name tag. c) The display can travel to the wrist to form a watch. d) The backside of the display shield exposes the IR beacon system and magnets for alignment with other displays. e) The Rovable with the attached display shield



Figure 12. Shape changing fabric. Robot self-attaches to fabric ends shifts to become a scarf according to temperature change.

Tactile Feedback

Core interactions: *Dragging tactor, point tactor.* Rovables can provide tactile feedback anywhere on the body. This is not possible with current wearable devices. To explore this idea, we designed a tactor that pokes the skin. The tactor is mounted on top of the Rovable, as shown in Figure 14. The tactor is driven by 136:1 miniature gear motor. A 3D-printed rack and pinion mechanism was used to convert the motor's circular motion into linear motion.

The pushing force from the linear actuator is around 1N. But since the robot vibrates with the linear actuator, the actual force applied to the human body is less than 1N. To make a more effective tactor in the future, some stabilization mechanism for the robot will be required.

LIMITATIONS AND FUTURE WORK

Navigation in 3D space: To be practical, wearable mobile robots will require accurate navigation in 3D space. In this paper, we developed and presented limited navigation on planar sheets of fabric. We believe that our approach can be translated into full 3D space. This will require more complex localization algorithms (e.g. Kalman filter) on board the robots. Our current microcontroller does not have enough processing



Figure 13. Interactive moving jewelry. Robotic brooch moves to become a shoulder microphone speaker when wearer receives phone call.

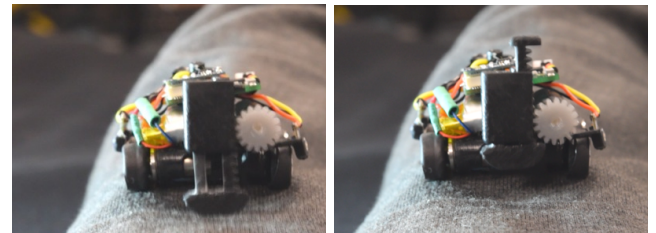


Figure 14. Tactile feedback application. We designed a linear actuator that can poke the skin. This tactor can go up and down to create tactile feedback.

power or memory to implement such algorithms. Fortunately, more advanced microcontrollers (e.g., 32bit ARM) are readily available. In future work, we plan to implement a full 3D localization and path planning algorithms.

Roaming on the on-body: The robots are presented with the challenge of roaming on an on-body surface, i.e., fabric. Currently, the robots are most reliable roaming on the torso. We experimented with roaming on cylindrical body surfaces such as the arm, however, it presented two major challenges (1) reliable navigation, and (2) overcoming clothing structures (e.g., seams). This requires further iteration and testing of the software control system to adapt to such surfaces, and perhaps basic alterations to clothing to achieve smooth movement. In the future we plan to test Rovables on the lower body and micro-locations such as the curvature of the neck, enabling truly seamless movement throughout the body. Further experimentation with fabrics and tailoring techniques unique to body locations will also be explored to remove all clothing-related barriers to movement.

Usability Currently, Rovables require a magnet on the back of the fabric. This limits the thickness of the fabric and can create a sensation from the magnet moving against the skin. In the future work, we plan to use a different locomotion method, that does not require anything on the back. For example, using biologically inspired burr-like materials on the wheels. The size of the robots can be reduced. Smaller motors and electronics can be obtained.

Perception The focus of this paper was on building the technology and exploring interaction space with applications. In the future, we plan to do user studies to understand the us-

ability of this technology better. The participants would wear the robots for a few days, as they go about their everyday life. This will give some insight on how the robots should behave to be unobtrusive and useful. This will require further technical developments such as improving the navigation algorithms and decreasing the size of the robots.

Utility of on-body robots Although it is early to name the killer applications, we envision that continuous monitoring of physiological data could be important. Throughout the day, robots can gather information such as full-body motion tracking, heart rate, muscle activity, and skin lesions. The information could be used for medical as well as lifestyle applications (sports feedback, accurate calories). With the current technologies, it is not practical to do extensive monitoring, as healthy users would not want to wear and maintain a large number of devices. Also, the users might forget to wear the sensors or wear them in the wrong place. Furthermore, the robots will perform functions of the current wearable electronics (e.g. watches, smartphones), so the users will be motivated to wear them. We will attempt to explore continuous monitoring in future works, as our technology needs to be developed further to do so reliably. Also, we hope that this work will inspire researchers to explore and develop new applications with wearable robots beyond the ones described in the paper.

CONCLUSION

In this paper, we introduced Rovables: miniature robots that can move on unmodified clothing. We propose the possible interaction scenarios and provide some example applications. We describe how such robotic system would function and the blocks needed to develop it. Some problems were easier to solve, such as power, since robots can wirelessly charge at the base station. The most difficult problems are finding the right locomotion mechanism and autonomous navigation in 3D space. Our attempts provide a working solution but are yet to be practical for everyday use.

In the future we imagine swarms of fingernail-sized robots moving autonomously around the clothing. Such robots will adapt to the user's style and preferences; appear and disappear seamlessly to do a variety of tasks. For example, such robots can form a wristwatch when you look at your wrist and otherwise disperse to do health sensing all over the body or become a decoration. Following the vision of Ubiquitous Computing, this is one way for technology to become invisible and weave itself into our environment.

ACKNOWLEDGMENTS

We thank undergraduate researchers Lucas Santana, Karla-Sofia Zapata-Garcia, Cheyenne Hua, and Diana Lamaute for help with implementation, Michael Chuah for mechanical structure advice, Oksana Anilionyte for garment construction advice, and Jie Qi and Nan Zhao for feedback on the paper.

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