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IEEE RA-L submission 19-1511.1

Mobile and Inflatable Interface for Human Robot Interaction

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Abstract— **Researchers hypothesize that networked physical robots may efficiently and safely manage large crowds in scenarios ranging from festivals and conventions to building evacuation. These scenarios pose a unique combination of hardware constraints involving safety for human contact, durability to withstand physical interaction, agility to keep up with moving crowds in non-trivial terrains, versatility to adapt to the situation and audience, and low cost to permit mass deployment. Here, we present a new mobile robot platform composed of a small rover base and a soft human-scale inflatable interface, capable of visual, tactile, and audible interaction with a variety of layman users. The inflatable interface allows the robot to maneuver discretely or in confined spaces when deflated, yet grow to encourage interaction; it combines an internal projector, a camera, and speakers, to emit and receive user information. The rover base is designed to keep up with humans at jogging speeds over relatively uneven terrain. Low weight further permits easy handling and transport. The entire robot costs less than $1.5K, and can serve as a general purpose test platform for a range of future human-robot interaction research.**

I. INTRODUCTION

Populated settings such as festivals and museums call for efficient crowd management and information distribution. Researchers in the human-robot interaction (HRI) domain hypothesize that such a job may be performed well by autonomous mobile robots providing guidance or simply a situational overview. Such robots would hold special advantage in emergency situations, where deployment of human rescue workers poses added risks. We already see a similar trend in the commercial space, where human informants are replaced with robot receptionists, concierges, and waiters [1].

The field of HRI has focused mostly on the design of personable and intuitive user interfaces as well as high level autonomy and intent interpretation for such service robots [2], [3]. The design of the actual robot platforms is left largely to industry, and correspondingly there are a wide variety of robot informants available on the market, spanning applications from health care proxies to social companions, and a wide range of autonomy, price, size, and capability (Fig. 1). However, the majority of these platforms are rigid, expensive, slow or immobile, of fixed morphology, and restricted to indoor locomotion limiting their use to researchers who wish to explore interaction patterns in less structured settings. We argue that deployment of autonomous mobile robots for crowd management poses a unique combination of hardware constraints beyond the reach of existing robot platforms, including:

- **Multi-modal interaction.** Research has shown that active engagement of humans benefit drastically from more than standard visual displays [4], [5].
- **Safe interaction.** A simple way to ensure safe interaction is to rely on soft interfaces, as inspired by the field of soft robotics [6].
- **Adaptability.** To engage with a diverse audience, the platform must have an easily adaptable interface and be capable of changing its form factor [7].
- **Agility.** The robot must be able to move rapidly alongside people over uneven terrains and potentially in confined spaces [8].
- **Durability.** The robot must have sufficient battery life and require little maintenance, despite harsh environments or treatment.
- **Low cost.** To permit mass deployment, customization, and easy adoption in research labs the robot must remain low cost, and easy to adapt and modify.

To comply with these constraints, we introduce a new HRI platform consisting of an interactive inflatable interface mounted on top of a rover base (Fig. 2.A). Engagement and interaction is facilitated through mobility, growth, image projections, audio, gesture-based, and tactile feedback. The platform provides a relatively safe means of interaction through a soft inflatable interface; the rover itself weighs less than 3.5 kg and is unlikely to cause impact damage. The size of the inflatable interface and the projected image can be adjusted to fit the user. The rover can move at a maximum

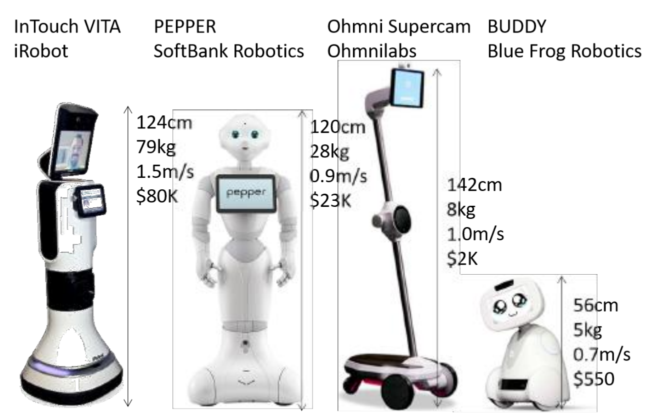

Fig. 1: Service sector robots span a wide range of applications, prices, sizes, and capabilities.

Funding for this research was provided by the NSF award number 1830471 and GETTYLABS.

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Preprint submitted to IEEE Robotics and Automation Letters as Submission for RA-L and ICRA
Received September 10, 2019 20:22:59 PST

speed of 1.5 m/s, corresponding to average human jogging speed. In deflated state, the height and diameter of the rover is 38 and 40 cm respectively, and the weight is located at the base permitting agile motion in confined spaces and on-axis turns. The rover can maneuver relatively rough terrains, such as carpets, tiles, and lawns; and easily traverse small obstacles such as uneven door frames and ramps. Because of its low weight, it is also easy for a user to pick up and carry past stairs or debris for example. The robot is low maintenance: it is equipped with impact absorbing foam and can withstand relatively rough handling and the battery lasts approximately 1 hour. Finally, the platform is made mostly from off-the-shelf parts and is at the lower end of the cost spectrum at just \$1.5K, which permits general deployment and easy adoption in research labs.

The closest related platform reported in literature is the Puffy robot [9], an inflatable robot of similar appearance to the main character in the Big Hero 6 Disney movie, mounted on an iRobot® Create, designed for Children with neuro developmental disorders. However, given our focus on a more general audience and deployment in crowds, the robot introduced here has a range of additional advantages in terms of interface adaptability, agility, and cost.

Note that the research reported in this paper does not extend to display - or interactive design, nor to the challenge of safe navigation, but rather focuses on the design of a general purpose hardware platform for receiving and providing information in an easy and intuitive manner. Moreover, this paper addresses how the robot's functionality pertains directly to developers/researchers in the field of HRI (referred to throughout as the "user") and to the human subjects of HRI research or real life use cases (referred to as "human agents"). In Secs. II- IV we present the rover design, inflatable interface design, and software architecture respectively. Additionally, we demonstrate and discus the performance of the robot in each section. Sec. V concludes and alludes to future work.

II. ROVER PLATFORM

The rover combines several modules which we briefly describe in the following and in Table I. Beyond the specific functionalities listed in the introduction, our design focus was on price, weight, durability and battery consumption, and ease of fabrication. With the exception of the power distribution board and the mechanical mounts for the time-of-flight sensors and inflatable interface, all components are off-the-shelf and easily obtainable. We further highlight where savings can be made, with additional fabrication time. The hardware architecture is highly modular and extendable, and additional sensors/actuators can easily be added through SPI or UART interfaces. Figure 4 shows an overview of the the rover hardware, including communication protocols between subsystems.

Chassis. The rover chassis is based on a 4 wheel drive all-terrain vehicle from Dagu Electronics. The chassis has a built in suspension which permits navigation over relatively rough terrain (Fig. 3); if this is not needed, the entire chassis

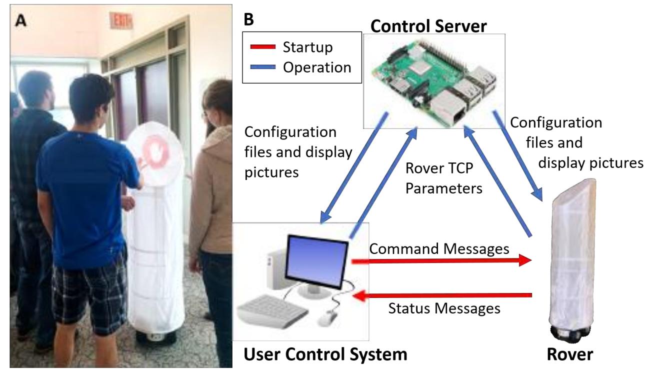

Fig. 2: A) We present an inexpensive, light weight, durable, and relatively fast remote-controlled mobile platform for visual, audible, and safe tactile human-robot interaction. B) Upon startup, the rover transmits TCP parameters to the control server and retrieves configurable files needed during runtime. The user control system retrieves the TCP parameters and creates a direct connection with the rover to control it.

Fig. 3: The Dagu Wild Thumber 4WD All Terrain chassis gives the rover mobility over relatively rough terrain as well as conventional HRI lab spaces such as carpet and tile.

kit could easily be replaced with a simpler and cheaper design. To support 1.5 m/s speed while loaded, we replaced the kit motors with 37Dx52L mm 30:1 metal gear motors from Pololu and use two high-power motor controllers from Pololu to create differential steering. A 3-cell 5.2Ah LiPo battery pack enables the rover to operate continuously for about 1 hour. Realistically, the rover will last much longer in experiments where it will often be interacting with users while stationary.

Computation and Builtin Sensors. The core of the robot platform revolves around an Intel Aero Compute Board®. Traditionally used with autonomous drones, this board features the Intel Atom x7-Z8750 quadcore processor with clock speeds up to 2.56 GHz, an onboard intertial measurement unit (IMU), Wi-Fi, interfaces to multiple cameras and other I/O, and is light weight and relatively cheap. All of the sub-modules are eventually controlled through the Aero board. The Intel Aero board is also equipped with an Alera MAX10 FPGA. Currently, the rover does not leverage this FPGA in its software architecture, but it could be leveraged in future work for accelerating computational tasks, e.g. image

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Received September 10, 2019 20:22:59 PST

processing or other forms of signal processing.

Control. Upon initialization, the rover transmits its Transmission Control Protocol (TCP) parameters (IP address and port) to the Control Server which maintains a static IP address. This allows the user's control platform to retrieve these parameters and establish a direct TCP connection to the rover, even while operating with a wireless network that dynamically assigns a IP addresses as is common at many academic institutions (Fig. 2.B). This design permits the user to simultaneously operate multiple rovers with dynamic IP addresses within the same wireless network. The Control Server also acts as a platform for the user to upload custom configuration files, photos for the rover to display, text for text-to-speech audio, and any other data files needed by the rover during operation. As detailed in Sec. IV, we set up the rover to be controlled by either a Bluetooth joystick through a laptop or controlled directly by a computer running, e.g. ROS for higher level control.

Information to the User. We integrate several means to convey information to the user. Most importantly, we mount a P300 Neo Pico projector from AAXA to project information onto the inflatable interface. This projector was chosen for its low weight, built in battery (2.5 hrs), and high light intensity (420 lumens). Second, we hooked up a small speaker for audible stimulus. Finally, the designer can use robot mobility or customized inflatable of the interface as detailed in Sec. III to attract the attention of nearby users.

Information from the User. We rely solely on vision to receive information from the user. Specifically, we make use of the Intel Aero Vision Accessory kit, which comes with an Intel© RealSense™ R200 RGB-D camera, an 8 MP RGB camera, and a high-speed, low resolution monochrome camera. We mount the RGB-D camera inside the inflatable interface to provide feedback on interface inflation state, as well as external user-engagement through simple contact shadow observation. We mount the RGB camera in front of the rover pointing upwards. In future work,this camera can be used to detect the presence and gaze direction of nearby potential users. Similarly, the monochrome camera is not currently used, but could potentially be used to support SLAM (simultaneous localization and mapping) in the future.

Other Sensors. Although we expect most of the higher level reasoning to come from off-board the robot, we implement a few local features to ensure low maintenance requirements. First, the Aero board features an onboard IMU, which we use to detect and correct the robot in case it is flipped over. We further hook up a separate Arduino Pro Mini board to control with the inflatable interface (Sec. III) and external Time-of-Flight (ToF) sensors mounted in the front of the robot to prevent collisions. The latter is especially important in crowded dynamic scenarios where many people are crowding around the robot.

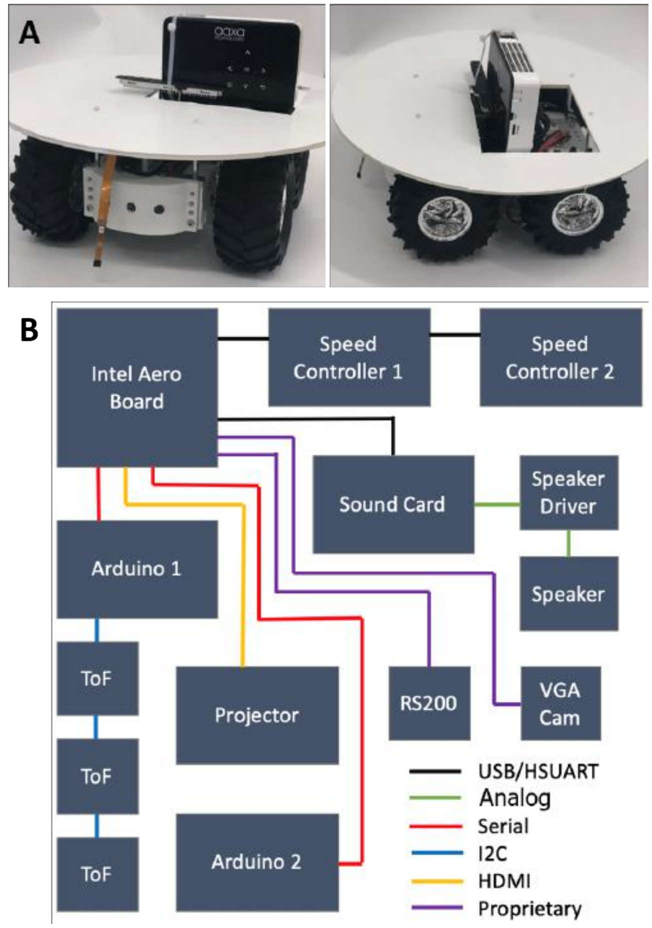

Fig. 4: A) Front and side view photos of the rover without the inflatable interface, showing ToF-sensors, front facing camera (normally mounted on the base plate), and projector. B) Overview of hardware architecture and communication protocols. *Arduino 1* is used as an I2C bridge for communication between the Intel Aero Compute Board and the three ToF-sensors. *Arduino 2* is used to control the pulleys, valves, and pumps that actuate the inflatable interface.

III. INFLATABLE INTERFACE

We complement the rover design with a soft, visual-touch interface for improving collaboration in ad-hoc human-robot swarms. The interface consists of a soft, inflatable, podium-shaped canvas with an internal camera-projector pair; beyond the audible feedback from the rover, such camera-projector systems have been shown to effectively gain the attention of a human audience [10]. In this section we focus specifically on the design and fabrication of the inflatable interface. The field of soft robotics has shown that soft components have many advantages over rigid components in robots which engage in human interaction [6]. The inherent compliance of soft robots ensure safety during interaction; fluid-driven interfaces such as this one furthermore permit visual and morphological changes that can be adapted to the user in question; finally, soft interfaces, like soft robots, may be cheaper and simpler to manufacture than their rigid counterparts. The current inflatable interface with driver circuits costs ∼\$150.

TABLE I: Component Overview

Component	Weight	Price
• 4WD Wild Thumper chassis, Dagu Electronics	1290g	\$180
• 4 × 30:1 Metal gearmotor 37Dx52L mm, Pololu	760g	\$100
• 2 × Simple high power motor controller 18v15, Pololu	28g	\$96
• 3-Cell 11.1V 5200mAh 50C Lipo battery, PowerHobby	350g	\$48
• Aero compute board, Intel®	60g	\$399
• Aero vision accessory kit, Intel®	24	\$149
• 4-Port USB hub, MakerSpot	35	\$14
• P300 Neo projector, AAXA	381g	\$279
• 1W 8Ω Mini loudspeaker, Uxcell	10g	\$3
• USB Audio adapter, Cable Matters	11g	\$5
• Pro Mini 328 - 3.3V/8MHz, Arduino	2g	\$13
• 3 × VL53L0X Time of flight, Adafruit	4g	\$45
• Ripstop nylon, Emmakites	130g	\$9
• 3 × 6V Mini air pump, Diminus	180g	\$43
• 3 × 298:1 HP Micro metal gearmotor, Pololu	28.5	\$48
• 3 × 6V 3 mm Solenoid electromagnet valve, Uxcell	15g	\$20
• Cables, tubing, and miscellaneous	127g	\$10
Total	3435.5g	\$1461

Human-scale inflatables have been deployed previously [11], however the need for them to act on a mobile base and as an adaptive interface is new. Beyond serving as a soft interface, the canvas itself can be inflated during run-time to a size which is easily noticeable in crowded environments (1.5m tall) and allows for comfortable human interaction; and deflated to a compact size (38cm tall) which enables the rover to be carried by an average-sized adult over obstacles such as stairs or rubble. Once the obstacle is traversed, the rover can inflate and continue normal operation.

The design of the inflatable interface with components is shown in Fig. 5. The interface consists of an outer cladding of light weight, white Ripstop Nylon (48g/m^2), which reduces the overall weight of the rover, while still protecting the internals against tears, dust, water, etc. The canvas has sown-in pockets that house 3 horizontal flexible PLA rings for stability and six vertical air channels for inflation. The air channels are made of PTE plastic (3” diameter) and welded using a Flexzion Impulse Sealer according to the instructions in [12]. Airtight seals between the PTE channels and the flexible tubing connecting to the pumps were achieved by adding an o-ring style contraption at the outlet, made from a sleeve of Ecoflex 30-00 silicone and a zip tie, also shown in the inset photo in Fig. 5.A.

The inflatable interface and driver circuitry is mounted to the rover via a magnetic snap-in base plate, which makes servicing and charging easy. The configuration of the interface driver circuitry on this base plate is shown in Fig. 5.B. An Arduino communicates via a two-wire-interface with the

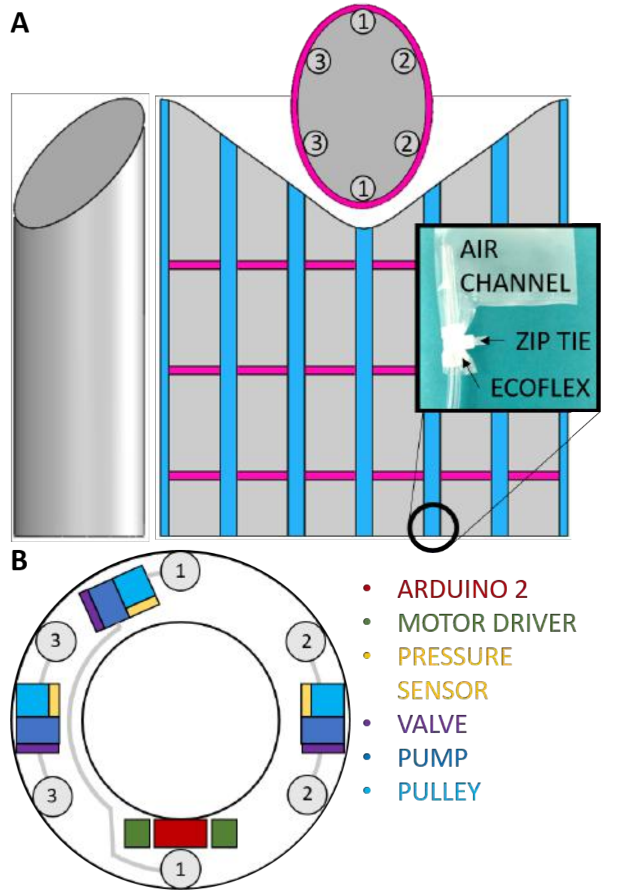

Fig. 5: A) Inflatable interface stitching pattern - the inset photo shows the air channel attachment, B) Configuration of inflatable interface driver electronics.

main rover and controls 3 pairs of pumps, pulleys, valves, and pressure sensors. The channels are connected in pairs to save on both cost and weight. The pumps used are DIMINUS DC 6V Mini Air Pumps and can inflate the canvas in ∼1 min at full speed. Despite their small size and low price, the pumps are powerful enough to burst the air channels (measured at 148 kPa), consequently, we use pressure sensors, MPXHZ6250 from Freescale Semiconductors, with an absolute range of 20 to 250 kPa for feedback control during inflation. To deflate the interface we activate three 5V normally-closed solenoid valves from Uxcell, and three pulleys tethered in tension to the upper PLA ring. These pulleys are driven by Micro Metal Gear motors from Pololu (1000:1). This allows us to inflate/deflate the interface to an arbitrary height to accommodate the user. Full deflation, similar to inflation, also takes 1 minute.

Beyond acting as a touch and visual interface for conveying and receiving information, the interface may be used for other important functions in crowded environments. First, its size enables the rover to perform obtrusive maneuvers such as blocking off doorways and redirecting traffic. The fully inflated interface can display detour signs in conjunction with auditory cues to help direct humans away from unsafe rooms or corridors. Additionally, we hypothesize that asymmetric inflation of the air channels inside the canvas could help the rover to self-right after it has been flipped over. The rover could use either the RGB-D camera, the regular camera, or the on-board IMU to detect such an occurrence. It is also possible that collaborative rovers are able to carry heavy loads safely on top of their inflatable interfaces. In the future the inflatable interface may further be adapted to include changing textures, similar to [13], for increased means of interaction.

IV. SOFTWARE ARCHITECTURE

The rover implements a highly modular multi-threaded software architecture (Fig. 6) written in Python3 that allows researchers and developers to program custom operational capabilities. The goal of this architecture is to be robust and efficient while minimizing the effort needed to develop new functionality. This section summarizes significant software components and capabilities of this architecture.

A Thread Manager spawns and monitors all computing threads on the rover. It ensures that a bug in one thread does not cause parallel threads to crash. The TCP Manager receives and enqueues all incoming Command Messages in the Command Priority Queue. All commands are encoded using JavaScript Object Notation (JSON) and contain information about the sender and command priority level. In cases where incoming Command Messages exceed the computational ability of the Intel Aero board, the Command Priority Queue ensures that commands are executed in user specified priority order. Command Messages of equal priority are executed in the order they are received. This, in conjunction with TCP's out-of-order delivery prevention, makes for a robust messages transmission and execution protocol.

The Command Executor processes each Command Message by looking up the command's associated Command Module (callback function) and executing it in a new Command Thread. All Command Modules are registered in the Command Registry. Command Threads are executed in parallel, leveraging all four cores of the Intel Atom processor. Basic controls, such as driving commands, projector images, camera feeds, etc., have pre-programmed Command

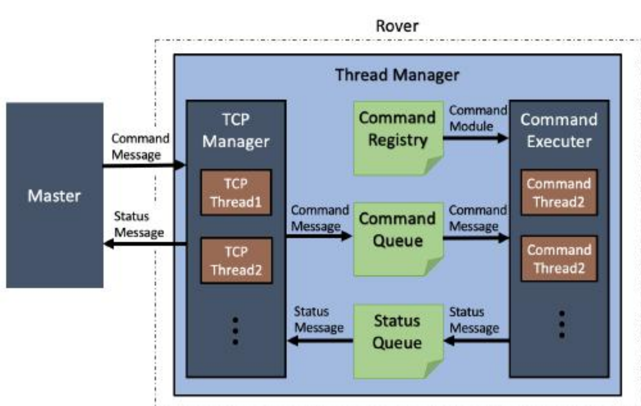

Fig. 6: Service sector robots span a wide range of applications, prices, sizes, and capabilities.

TABLE II: Thread and Command Module Overview

Command Module	**Description**
Text-to-Speech	Rover dictates audible messages through speakers
Fetch external camera image	Captures image from external camera
Fetch internal camera image	Captures image from camera inside of inflatable interface
Project	Changes visual display
Get image names	Returns a list of all display images in database
Set speed	Adjusts speed of left and right wheel motors
ToF sensors	Returns readings from time of flight sensors
Read IMU	Returns readings from internal IMU
Inflate/deflate	Controls inflatable interface state
Check for command	Always running; monitors and maintains command queue
TCP Thread	**Description**
Listen	Receive and enqueues incoming command messages
Check new IP	Monitors IP of rover and updates Pi Server
Check status queue	Monitors and maintains status queue

Message and Command Modules (Table II). User-specific functionality, such as new sensors, maneuvers, interfaces, etc., must be implemented in a new Command Module and registered with the Command Registry. Upon execution, each Command Module returns a Status Message which the Command Executor adds to the Status Queue to be processed by the TCP Manager. The TCP Manager sends these Status Messages back to the user control platform over the same socket as incoming messages. These Status Messages help to maintain robustness by informing the control platform if there is a problem during the execution of a Command Module. Lastly, the rover asserts a software interface to ensure that user defined Command Messages, Command Modules, and Status Messages are properly implemented. The remainder of this section highlights two of the key software functionalities of the rover.

Text-to-speech. Traditional alarm tones, such as beeping, can be unclear and misinterpreted as there is no universally accepted interpretation for non-verbal alert sounds. This problem can exacerbated by the high stress conditions of evacuation and emergency scenarios. Further more, it has been shown that verbal material presented auditorily is better remembered than the same material presented visually [14]. We therefore implemented an offline TTS (text-to-speech) engine, called pyttsx3, to convey verbal information to the people in its vicinity.

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Received September 10, 2019 20:22:59 PST

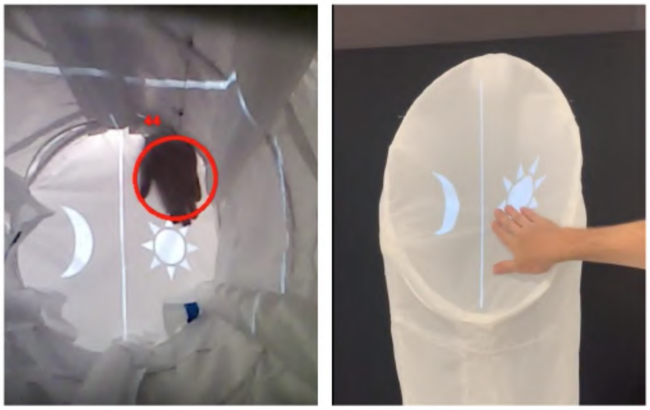

Fig. 7: The rover implements a simple contact shadow detection algorithm to sense when and where a human is touching the inflatable interface. This allows for input from the user.

Gesture Recognition. We use the projector to display information and visual buttons on the top surface of the inflatable interface. The internal camera and a contact shadow detection algorithm is used to identify when and where a user is touching this interface. The rover uses OpenCV [15], an open source Python-based image processing library, to perform a number of image transformations including thresholds, Gaussian blur, erosion, and dilation. Sci-kit Image, another open source Python library, is then used to identify groups of pixels that are potential contact shadows. Lastly, these groups of pixels are fit into contours that are identified by an OpenCV implementation of an algorithm proposed in [16]. These contours are then paired down using empirically determined criteria to identify the location of a contact shadow on the canvas. The processing frame rate can be configured by the researcher to tailor computational resource consumption. While this algorithm only leverages deterministic image processing techniques, it could be made more robust in future work by implementing convolution neural networks (CNN) for contact shadow detection. For example, the use of a CNN could prove to increase robustness in cases of extreme lighting conditions, or help to better identify features of the human hand; filtering out contact shadows cast by other objects. In future work, we hope to implement further gesture recognition capabilities, such as swiping and scrolling using the dynamic position of the user's hand.

V. CONCLUSION AND FUTURE WORK

We introduced a new HRI platform, that is especially targeted to adhoc human-robot swarms in crowded settings. The platform is relatively inexpensive ($<$ \$1.5K), fast to fabricate with mostly off-the-shelf components ($<$ 1 week), and built in a modular fashion to ease adaptation to new academic studies. Specifically, we showed that the remote-controlled platform is capable of movement over various terrains (tiles, carpet, grass) with a top speed of 1.5 m/s; enable easy manual transport with 3.5 kg total weight; is capable of changing morphology from a compact form factor of 1.5 m to less than 0.4 m height in 1 minute; and exhibits audible, visual, and haptic interaction.

In the future, we hope to improve the repeatability and speed of the interface inflation/deflation; and more importantly look into additional capabilities enabled by the inflatable interface including texture change for more interesting haptic feedback, the ability to collectively lift debris or transport loads safely on the inflatable interface, and rover self-righting abilities in case it falls over. The contribution of this work, therefore lies in the high level system design and multi-faceted use of and integration of components to produce a general purpose, easily customizable, relatively inexpensive and agile robot platform, lowering the barrier of entry to HRI studies with several users in non-static settings.

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