Prototyping Robot Appearance, Movement, and Interactions Using Flexible 3D Printing and Air Pressure Sensors

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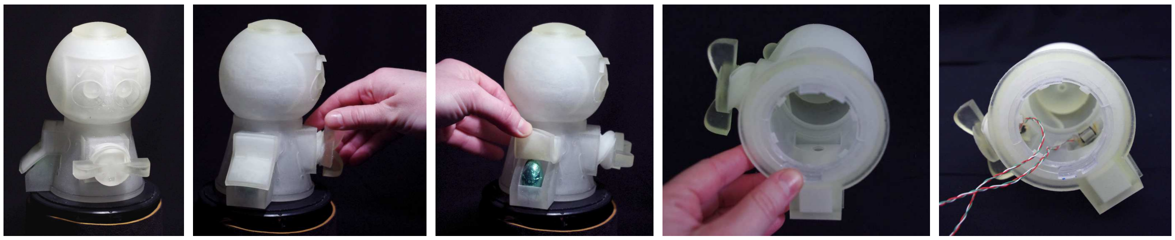

(a) Front view (b) Twisting the handle (c) Bending the flap (d) Inside view (e) Inside view with sensors

Fig. 1. Lucifer the Gumball Machine, 3D printed with a flexible rubber-like material. Air pressure sensors plugged into hollows in the twist handle and door flap capture interactions.

***Abstract*— We present a method for rapidly prototyping interactive robot skins using flexible 3D printed material and analogue air pressure sensors. We describe a set of building blocks for presenting affordances for different manipulations (twist, bend, stretch, etc.). Each building block is a hollow air chamber that can be printed as an integral part of the skin to easily add sensing capabilities over any broad area. Changes in volume caused by manipulating the chambers are captured using air pressure sensors; the sensors can be plugged in and removed, allowing rapid iteration on new designs. We demonstrate our method by prototyping three robot skins that attach to the Keepon Pro armature. With fully operational robot skins, we can study the dependencies between appearance, movement, and interactions at a deeper level than would previously be possible at the concept stage.**

I. INTRODUCTION

The appearance of a robot is critical to its acceptance; studies have shown that humans will "intuit" factors such as personality [1], intent [2], and intelligence [3] solely from the external look of a robot. Our tendency to make these subjective judgments makes it crucial that all aspects of a robot's appearance, from the broad shape of the body to the subtle tilt of the eyes, are refined until they convey the image desired.

In addition to appearance, the motion of the robot is critical to human perception; motion parameters such as acceleration and curvature [4], music synchrony [5], inclusion of gestures [6] or expressions [7], and even unintended cues like motor noise [8] all affect a human's perception of the robot. Mori postulated that our acceptance of a robot form increases with its increasing similarity to humans, up to a point at which even slight deviations cause a sense of uncanniness [9]. He further hypothesized that the uncanny valley's peaks are exaggerated for a moving robot, showing the importance of motion to robot acceptance.

Ishiguru extended Mori's uncanny valley graph with a third axis, similarity of behavior [10]. He argued that "humans expect balance between appearance and behavior when they recognize creatures". Maximum familiarity is achieved when a robot behaves congruently with expectations raised by its appearance. An important component of the behavior of a social robot is how it will respond to intended physical interactions, i.e. being pushed, squeezed, bent, or twisted. Where and how these interactions take place on the robot determine the affordances it will present to the world. Presentation of affordances is directly linked to robot appearance; and both appearance and interaction govern the space of movement. Our conclusion is that optimally, robot appearance, movement, and interaction would be designed in concert.

Creating flexible sensing skins for new robot actuation mechanisms is nontrivial, however. Casting a custom rubber skin requires a large investment in time and tooling; incorporating sensing often requires wiring swaths of point sensors over large areas. Thus studies on robot appearance and movement often rely on showing 2D images [1] or testing on limited appearances in the real world [4].

In this paper, we propose taking advantage of the power of rapid prototyping technology to open up new possibilities in robot design. With recent advances in 3D printing, robot parts can now be created out of a variety of materials, from hard to flexible to multi-colored, and intricate shapes and topologies constructed in a matter of hours.

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We prototype interactive robot skins by 3D printing them in flexible rubber-like material. The power to print intricate shapes enables a new way of incorporating sensing. We propose a set of building blocks, consisting of hollow chambers, that each register a particular manipulation, such as twist, bend, or stretch. These chambers are printed as an integral part of the skin. Manipulating a chamber changes its physical volume, and hence, its internal air pressure. We use off-the-shelf air pressure sensors plugged into the chambers to sense user interaction. The sensors are reusable in future prototypes.

We demonstrate our prototyping method by developing, from scratch, three robot skins that fit on the Keepon Pro armature: an anthropomorphic gumball machine, an interactive devil, and a ghost. The first two characters demonstrate different examples of our building blocks; the third one focuses on iterating between movement and appearance.

Due to the current cost of 3D printing and the limited print area, our method is currently most appropriate for small robotics. Our method can be used to do the following:

- Design the affordances for interaction. Our building blocks provide an easy way to incorporate buttons and robot limbs with different affordances.
- Create iterations of a small robot to improve the appeal of its look combined with its movement.
- Prototype interactions combined with simultaneous movement (e.g. response to a robot being petted) and see the overall effect.

In the next section, we review related work in sensing methodologies and rapid prototyping for robotics. We then discuss our method in more detail, presenting our building blocks. We describe our three robot skins, and then conclude.

II. Related Work

Flexible robot skins with attached or embedded sensors have been fabricated from several different materials. Conductive thread and conductive fabric were used by Inaba et al. to create a robot sensing suit [11]; Pan et al. quantify the accuracy of a textile position sensor [12]. Conductive textiles, while inexpensive, require labor-intensive hand-stitching for each new prototype; our method allows changes to be made in the 3D modeling program. Urethane foam was surrounded by a flexible circuit containing LEDs and phototransistors to create a multi-axis deformation sensor [13]. Silicone rubber has been attached to optical reflectors [14], piezoelectric polymers [15], or piezoresistive polymers [16]; and embedded with inductively coupled wireless sensors [17], acoustic resonant tensor cells [18], magnets [19], optical waveguides [20], or microstructures for capacitive sensing [21]. Air pressure has been prototyped for use in robot skins by embedding a wireless air pressure sensor in a silicone cavity [22]. Castable rubbers such as silicone are appropriate for use in the final product, with their ruggedness and skin-like feel, but the cost and effort required to create new molds and incorporate sensing elements makes them inconvenient for prototyping. As 3D printing becomes more widespread, the cost of the printing resin used in our method will continue to decline.

Rapid prototyping technology has been used for many years in designing jointed robots with rigid skeletons. "Rapid Prototyping for Robots" presents a good overview of previous work, with explanations of the various 3D printing processes and a database of moving joints made from rigid printable material [23]. Current trends include 3D printing conductive materials [24], tissue scaffolds [25], unusual materials [26], and embedded components [27].

III. Rapid Prototyping with Air Pressure Building Blocks

In our method, the designer builds a model of the robot in a 3D modeling program, designing portions that need to be touch-sensitive as hollow chambers, and prints the entire model using flexible rubber-like material. We built our models in SolidWorks and printed them using the TangoPlus material on an Objet Eden 260V.

As part of our method, we present a toolkit of building blocks, shown in Fig. 3, for creating different affordances as part of the robot skin. Our toolkit builds on the ideas of Slyper and colleagues, who design a set of "sensing structures" for capturing deformations in a soft solid material such as foam or silicone [28]. Our building blocks give the external shape of hollow chambers designed to be integrated into the robot skin. Each building block presents a given affordance, such as bend or twist, and deforms naturally when that manipulation is performed; some of the building blocks have stronger air pressure changes when the given motion is performed, and weaker response to other motions. Graphs of air pressure response for the accordion shape are given as an example in Fig. 4. The list of building blocks is a first step to a more extensive vocabulary of building blocks, each with different properties.

These chambers are printed with a small hole for insertion of a 3D printed plug holding the air pressure sensor. The hole also allows removal of support material (a wax-like, water-soluble substance used in the printing process to maintain structural stability while printing).

The plug, shown in Fig. 2, secures the sensor to a chamber wall. It is modeled in Solidworks and 3D printed with the same rubber-like material. The plug holds an off-the-shelf Freescale air pressure sensor, 0 to 10 kPa gauge. This range of pressure is suitable for registering typical light presses. Standard casings are used in Freescale's line of sensors, so sensors can be selected with a range appropriate to the scale of the prototype without modifying the plug. The air pressure

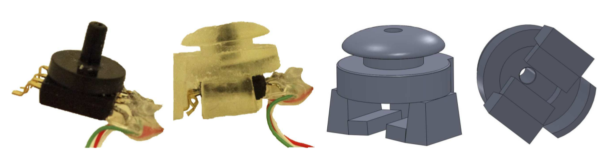


Fig. 2. The plug we designed to hold the air pressure sensor. *Left*, air pressure sensor, with and without cover; *Right*, renders of the plug.

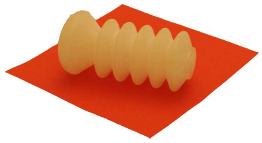
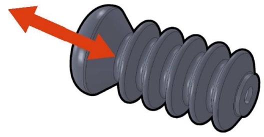
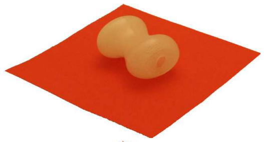
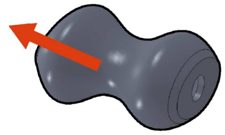
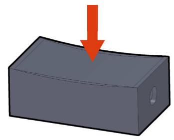
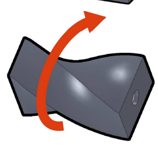
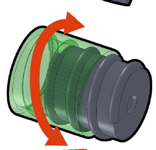
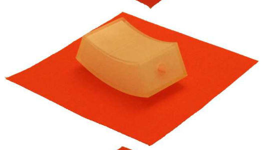
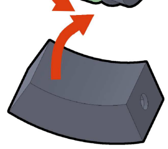
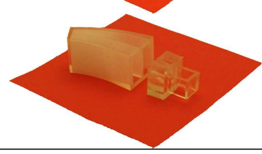
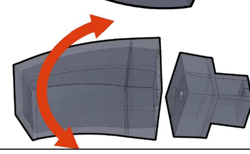
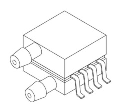
Manipulation	Printed Form	Digital Model	Explanation
Pull and push			In an accordion shape, air pressure responds to changes in volume caused by pushing (positive pressure) and pulling (negative pressure); squeezes and bends do not change volume significantly
Pull			A shape with a grip suggesting pulling
Press			The top indentation suggests pressing or squeezing; images of buttons could also be embossed on the surface in the modeling program
Twist			Twisting of this shape happens easily in only one direction and causes a large difference in air pressure; the shape buckles when bent, thus small bends do not register
Twist			Screw-together twist pieces can be 3D printed; pressure changes with volume when twisted
Bend			Although this shape will respond to both pressure and bend, the appearance encourages bend; this suggestion could be further enhanced with surface creases
Bidirectional bend			 Direction of bend can be measured by using two chambers, and a differential air pressure sensor with two input ports

Fig. 3. Our set of building blocks for prototyping sensing robot skins with various affordances. Each model has a hole to plug in an air pressure sensor.

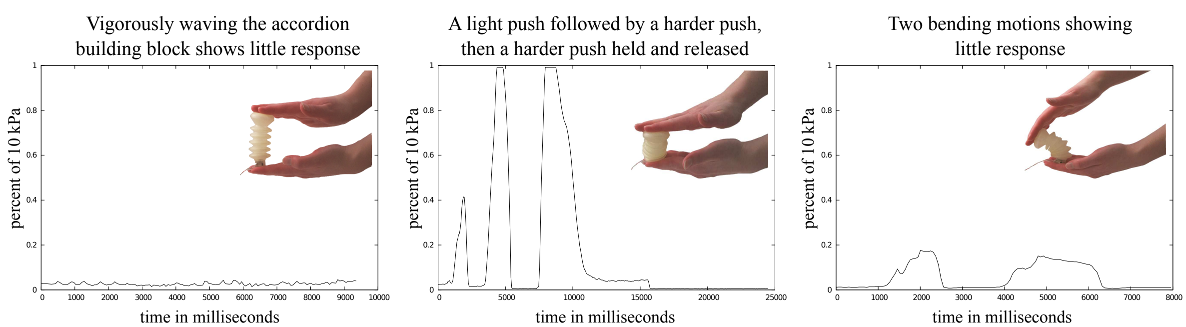


Fig. 4. Air pressure response to manipulations of the accordion building block.

sensors act as a sensing kit that can be re-plugged into each prototype robot, allowing quick, economical reuse of sensors.

Our plug's minimum diameter of $8.4mm$ fits tightly in $8mm$ holes in the robot skin. The air pressure sensor cannot be plugged directly into the building block, as the smaller $3mm$ hole for the sensor tip would make it difficult to remove support material.

The tactile feel of the chamber changes based on whether the seal between the plug and the robot skin is airtight. If the seal is leaky, the robot appendage is squishy, and requires recovery time to regain its shape. An airtight seal, made by gluing the plug to the chamber (while keeping the sensor removable), feels more like a firm balloon. The tactile feel can be customized to each application.

The rubber-like material is strong enough for attachment points (pockets, holes, etc.) to be printed as part of the prototype, allowing easy attachment to actuation armatures or rigid casings. We attach to the Keepon Pro armature, shown

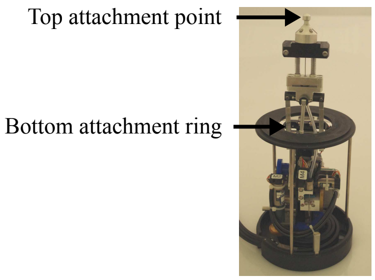


Fig. 5. The Keepon Pro armature.

in Fig. 5, by printing a socket in the head of our robots, and tabs along the bottom for aligning a rigid bracket.

Future 3D-printable materials will present a range of different rubber properties, and will have the durability to allow our method to be used to construct and instrument finished skins. The rubber-like TangoPlus material is suitable for prototyping, and may not exactly mimic the properties of the final robot skin. Silicone, for example, has quicker rebound and more stretch. Nevertheless, TangoPlus gives a rough idea of the final movement, and its thickness can be varied across the model to encourage the desired dynamics (e.g. inserting a crease to encourage deformation in a given area).

Our method takes advantage of the strengths of 3D printing. With a 3D model of the skin, designers can rapidly iterate on the design of the robot, and print skins with topologies that would be difficult to cast, such as the hollow chambers that make air-pressure sensing possible. When building our examples, we found it useful to print small-scale models to study the look of the character, before spending the printing resin on a full-scale prototype.

IV. Robot Skins

We next describe the construction of our three robot skins. We show that by prototyping the skins using our method, we have an easy way to incorporate various affordances, as well as a platform to test questions that spring from the interdependence between appearance, movement, and affordances. In each robot, we give an example of how our method helped improve the original design.

A. Robot Skin: Lucifer the Gumball Machine

Lucifer, an anthropomorphic old-fashioned gumball dispenser, uses our building blocks to sense twist in his coin handle and bend in his door flap, as shown in Fig. 6. An air pressure sensor is plugged into each of the two building blocks in the final version, shown in Fig. 1. Lucifer dances happily until a passerby twists his handle, whereupon he excitedly motions to them to lift the flap and take the concealed candy. If the passerby opens the flap first without "paying", Lucifer responds angrily, jerking the dispensing area away from the thief.

To conserve resources, we first printed hard-plastic miniatures to judge the look of each of our characters. Colleagues who saw our first gumball miniature, shown in Fig. 7 *left*, thought the ridges intended to indicate bendability of the door flap were a staircase. The hair (it would drape when printed in rubber) detracted too much from the bubblegum-machine appearance; the eyes were sufficient anthropomorphism.

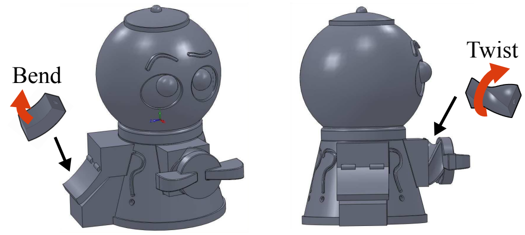


Fig. 6. Renders of the gumball machine model, showing our hollow building blocks.

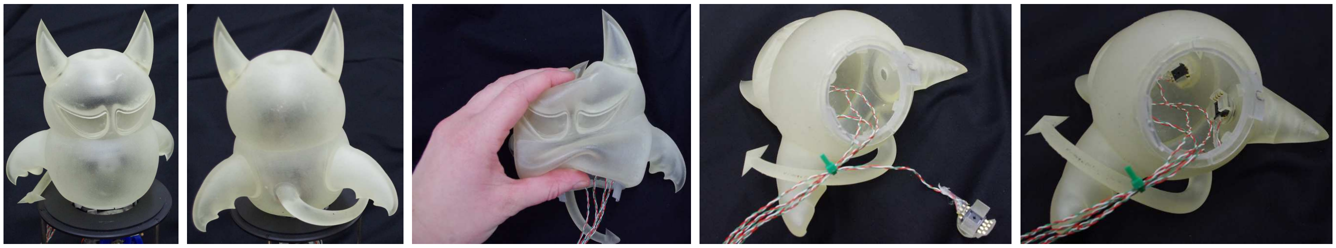
Fig. 7. Iterations revealed design flaws in appearance/affordance and affordance/motion.

Our first full sized prototype, shown in Fig. 7 *right*, revealed a flaw in the intended motion combined with the twist affordance. We had intended the entire body to be flexible when dancing, but with this prototype we could see that twisting the knob would cause the entire lower body to buckle unnaturally. In the final version, we stiffened the lower body by making it thicker, and moved all motion to the robot's head. With a multi-material printer, we could build the model out of a combination of rigid and flexible materials, better channeling the motion.

If we desired to fully develop this character, we would move into user testing, and continue to iterate on the skin with questions such as the following:

- Will passersby be bold enough to twist the handle? Should the robot hold still to appear less imposing? Will changing the friendliness of the appearance and/or motion better lure in bystanders?
- Does the handle need to be overly large, or have a "twist me!" sign on it, to make the affordance obvious? Will this constrain the robot's movements?

Our method provides the flexibility both to refine the design, perfecting the current gumball dispenser's performance, or to easily broaden the scope of the questions. Our building blocks could be swapped out: for example, with a simple change in the CAD software, the twist handle could become a pull ring or pushbutton. If the entire concept is flawed (perhaps today's children no longer recognize bubblegum dispensers), the entire body could be changed, incorporating the knowledge learned from the current movement and affordances: for example, we could switch to a robot toy vending machine with flap and buttons.



(a) Front view (b) Rear view (c) Deformation of the rubber-like material (d) Inside view (e) Inside view with plug and sensor installed in the wing

Fig. 8. Creepon the Baby Devil.

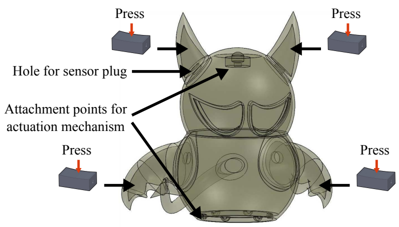


Fig. 9. A render of the Creepon model, with actuation attachment point, and hollows in the wings and horns visible.

Fig. 10. Iterating on the mouth shape of the talking ghost.

(a) Mouth closed (b) Mouth open and LED eyes on (c) Inside view

Fig. 11. Gus the Ghost.

B. Robot Skin: Creepon the Baby Devil

Creepon the Baby Devil, shown in Fig. 8 and Fig. 9, uses our air pressure method to make all its limbs sensitive to squeezing. As an example interaction, we test the feasibility of the piece of showmanship shown in the accompanying video: while Creepon tries to dance, a mischievous human repeatedly tweaks a limb and quickly hides, leaving Creepon to look around confusedly and get progressively angrier.

The interaction is entertaining, and the skin deforms significantly, enabling Creepon to dance fluidly and evince dejection and anger. One flaw with the concept was revealed, however: it took careful timing to grab hold of Creepon's small limbs when he was dancing, and mistiming it put stress on the Keepon Pro armature. In a future iteration, we could use this lesson to design bigger limbs that moved more flexibly where they joined the main body; or we could attack the movement and interaction, using a slower song with pauses. The solution could involve any of appearance, movement, and interaction; but the problem was only revealed when all three were combined in a working prototype.

C. Robot Skin: Gus the Talking Ghost

In our final example, we use our method to test a motion concept: designing a flexible robot whose mouth moves as if talking, although the actuation is transferred through the skin from the Keepon armature's top attachment point, as shown in Fig. 12.

Through iteration, we realized that the shape of the mouth was key to the illusion. Our first prototype of Gus the Ghost (Fig. 10 *left*) buckled near the mouth; we tried a thinner curving mouth to distribute the stress (*center*) but the rigidity caused the head to assume an oval shape when bent; our final iteration (*right*) used a wide, empty mouth with circular arcs on the edges, which would bend easily under stress, minimizing buckling. The final Gus, with controllable LEDs inside his eyes, is shown in Fig. 11.

V. Discussion and Conclusion

We have presented a method for rapidly prototyping flexible robot skins with easily incorporated sensing. The set of building blocks we developed provides guidelines for indicating and sensing various affordances.

Our method provides a full, working system throughout the prototyping process, thus allowing simultaneous iteration on appearance, movement, and interaction. We demonstrated this advantage by developing three robot characters, and describing needed modifications to the designs that only became apparent with a working system.

Our method has several practical limitations which currently restrict it to prototyping. The rubber-like material tears more easily than silicone. Tearing can be minimized by rounding all corners and edges, and the quality of 3D printing materials will continue to improve. The air pressure sensor size limits the possible density of sensing regions (sensors would bump into each other). In the future, we could move

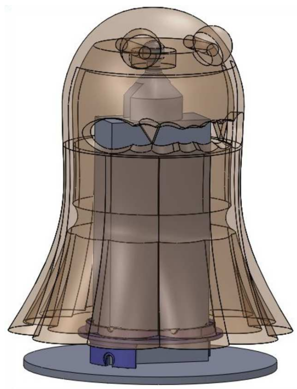


Fig. 12. A render of the ghost model assembled with the Keepon Pro armature, to test the fit.

the air pressure sensors outside the robot, routing the pressure using plastic tubing.

Our prototypes have practical uses besides iteration. We could control test conditions in robot appearance studies. Appearance changes could be made to a base model in software, and user interaction tested in the real world using the same robot mechanism and movement.

This paper presents one of many ways to harness the exciting possibilities enabled by rapid prototyping. Rapid prototyping is leading a "personal manufacturing revolution" where anyone can design and create their own goods. Our work could be expanded into a robot kit that allows anyone to use 3D printing services to build their own flexible robots. We envision the kit consisting of a generic robot armature with a set of pre-wired air pressure sensors, and software that would help select from among our building blocks and merge them into an existing 3D character model for printing.

Multi-material printers, combined with the promise of printable conductive material, are getting us closer to 3D printing a complete, interactive robot. New research will need to explore what types of integrated sensing and actuation such a system makes possible.

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