PaintPots: Low Cost, Accurate, Highly Customizable Potentiometers for Position Sensing

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Abstract— **The PaintPot manufacturing process is a new way to create low-cost, low-profile, highly customizable potentiometers for position sensing in robotic applications. It uses widely accessible materials, requires no special expertise, and creates custom potentiometers in a variety of shapes and sizes, including curved surfaces. PaintPots offer accuracy and precision performance comparable with commercial (non-customizable) options through a calibration process that trades small computation for cost.**

This paper includes detailed PaintPot manufacturing and calibration processes, and experiments that validate the accuracy, precision, and lifetime performance of PaintPots, comparable to commercial sensors. We also provide a case-study application in the SMORES-EP modular robot, and show how the PaintPot process can be used to create resistive surfaces capable of sensing position in 2D on planes and spheres.

I. Introduction

Nearly all robots with articulated joints require position sensing to precisely control their motions. Most commercial position sensors are available in a limited set of form factors, which constrain their positioning relative to the joint they are measuring. This can be a serious design challenge, especially in highly space-constrained applications like modular robots.

The PaintPots process is a novel method to create low-cost, low-profile, highly customizable potentiometers for position sensing. PaintPots can be made using widely accessible materials (spray paint and plastic sheet) and tools (laser cutter, or scissors), cost about $1 USD to make in small batches, and require no special expertise to manufacture. They are highly customizable in terms of shape, size, and surface curvature, and can be directly integrated with existing plastic surfaces on parts. Once calibrated, they provide accuracy and precision performance comparable to off-the-shelf commercial potentiometers of similar cost.

PaintPots open robot design to a broader audience, enabling designers to tightly integrate custom position sensors into their robots, even if they would not normally have the expertise or funding to do so. Recent research into low-cost and printable robotics provides ample motivation for such sensors [1], [2]. Beyond the realm of low-cost robotics, PaintPots offer sensing performance and customizability that makes them competitive with commercial potentiometers. As a case study, we present two PaintPots designs used in the SMORES-EP modular robot. Finally, we demonstrate how PaintPots enable 2D position sensing on arbitrary surfaces, including a plane and a sphere.

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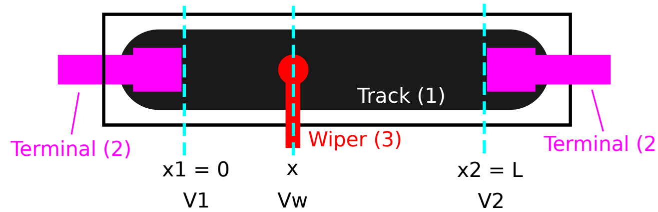

Fig. 1. Potentiometer schematic showing the three parts (track, terminals, and wiper) as well as position and voltage labels.

II. Related Work

A. Potentiometers

Potentiometers are three-terminal devices that can vary the resistance to a moving contact. The typical geometry is either a circular (*rotary pot*) or straight (*slide pot*). All potentiometers have the three basic components shown in Figure 1: (1) a resistive track, (2) fixed electrical terminals at the track ends, and (3) an electrical contact (wiper) that moves along the track surface. Most modern tracks are a continuous semiconductive surface made of graphite, ceramic-metal composites (cermets), conductive plastics, or conductive polymer pastes. PaintPots use an inexpensive carbon-embedded polymer spray paint for the track surface.

For position sensing applications such as robotic joint sensors, potentiometers are almost always configured as voltage dividers where each of the terminals are connected to a known voltage and the wiper voltage can be changed by moving between the two terminals.

Industrial processes are available that allow custom potentiometers to be created. Some electronics manufacturers offer inkjet-printed thick-films that can be deposited on printed circuit boards and other surfaces to form the tracks for custom potentiometer position sensors [3]. The primary distinguishing factors of the PaintPot method as compared to these processes are cost and time: these are industrial processes that often require thousands of dollars in up-front engineering fees, produce sensors that cost tens of dollars each, and have turnaround times of a week or more. Our method can be used by anyone, produces sensors that cost on the order of $1 USD per unit, and allows rapid iteration (limited only by the drying time of the paint).

B. Ubiquitous Electronics

Recent work on ubiquitous computing and robotics technologies often leverages rapid prototyping technologies to to allow electronics to be integrated into everyday objects at low cost. Miyashita *et al.* [4] introduce self-folding printable resistors, capacitors, and inductors made of cut sheets of aluminum-coated polyester film (mylar). An accordion-like variable resistor is presented, whose resistance changes as the folded layers are compressed and expanded. Kawahara *et al.* introduce Instant Inkjet Circuits [5], a technique for accurately printing low-resistances traces on sheet materials using silver nanoparticle ink deposited using a standard inkjet printer. This method has been used to explore designs for capacitive touch-sensitive sheets, which can be adapted to custom shapes by cutting with scissors [6]. Unlike PaintPots, a primary design concern for these silver-ink printed circuits is attaining sufficiently low trace resistances ($< 1\Omega$), as the printed conductors are intended for use as wires. In the case of PaintPots, relatively high resistances (on the order of $k\Omega$) are desirable, since the potentiometers are intended to be used as voltage dividers.

III. Background: Potentiometer characterization

A. Conformity (Accuracy)

The relationship between wiper position x and wiper voltage V_w (referring to Figure 1) is used to measure position. Let the function $V_w = f(x)$ be the *potentiometer model*. The degree to which $f(x)$ matches reality is referred to as *conformity*. Mathematically, *absolute conformity* is defined as the percent maximum deviation of the measured wiper voltage from the model over a defined travel range [7]:

$$\frac{|V_w(x) - f(x)|}{|V_w(x_2) - V_w(x_1)|} \leq C_{abs} \forall x \in [x_1, x_2]$$

Conformity measures accuracy: neglecting noise, it bounds the error relative to ground truth. Commonly, commercial potentiometers intended for position sensing are modeled as linear, that is: $f(x) = \left(\frac{V_2 - V_1}{x_2 - x_1}\right)(x - x_1) + V_1$ In this case, the term *linearity* is used in place of conformity.

B. Resolution

Resolution refers to the ability to register small changes in the value being measured. In practice, potentiometer resolution is often limited by the bit depth of the analog-to-digital converter used to read V_w. To compare PaintPot performance to off-the-shelf potentiometers, we are interested in measuring the intrinsic resolution of the device itself, independent of the analog-to-digital converter. Since potentiometers are analog devices, some manufacturers incorrectly list intrinsic resolution as infinite. In fact, the intrinsic resolution is determined by the mechanical noise properties of the strip material.

The *resolution limit* of a measurement system is w_{res} if there is an equal probability that the indicated value of any measurement whose actual value differs from a reference by less than w_{res} will be the same as as the indicated value of the reference [8]. Novotechnik Inc. introduce the concept of Relative Gradient Variation (RGV), which can be used to determine the resolution limit w_{res} of a potentiometer [9]. RGV provides a measure of local deviations in resistance caused by material fluctuations at small length scales (typically micrometers). Consider a one-dimensional straight-line potentiometer configured as a voltage divider, as shown in Fig 1. Let V be the wiper voltage, and x be the wiper position as it travels from $x_1 = 0$ to $x_2 = L$. As the wiper is moved, the *gradient* at position x can be defined $g = \frac{dV}{dx}(x)$. The *mean gradient* over a region $[x_1, x_2]$ can be defined $\bar{g} = \frac{V(x_2) - V(x_1)}{x_2 - x_1}$. *RGV* at $x \in [x_1, x_2]$ with window size w is defined:

$$RGV(x, w) = \frac{\frac{1}{w}\left(V(x + w/2) - V(x - w/2)\right) - \bar{g}}{\bar{g}}$$

RGV compares the local gradient in the window $x \pm w/2$ to the mean gradient of the sensor. Intuitively, RGV measures how much the behavior of the sensor in a small region (the local gradient in $x \pm w/2$) deviates from the nominal model (the mean gradient $\bar{g}$). Local deviations in gradient are due to fluctuations in the material properties of the potentiometer track at the microscale. As window size increases, we should expect RGV to decrease, since these small fluctuations will tend to cancel each other out (by the central limit theorem), and when $w = x_2 - x_1$, $RGV(x, w) = 0$ by definition. Conversely, as w decreases, RGV will increase.

Using RGV, we can compute the resolution limit w_{res} of a potentiometer. If for some sufficiently small w, $RGV(x, w) = 1$, this means the local variation in gradient is comparable to the mean gradient, so we know that in the region $x \pm w/2$, a change in the output signal of the potentiometer is just as likely to represent a fluctuation in local material properties as an actual movement of the wiper. Thus, $w = w_{res}$ is the resolution limit of the potentiometer [9].

Assume we have collected a dataset $\mathbf{V} = \{V_0, V_1, \ldots V_N\}$ which is a digitally sampled representation of $V(x)$ at points $\mathbf{X} = \{x_0, x_1, \ldots x_n\}$. Selecting a window size w, we may compute the mean absolute RGV for the sample:

$$\overline{|RGV|}(w) = \frac{1}{N}\sum_{i=0}^{N}|RGV(x_i, w)|$$

The resolution limit w_{res} is the window size for which $\overline{|RGV|}(w_{res}) = 1$.

Potentiometer performance is sometimes characterized in terms of "smoothness," a metric which is qualitatively similar to resolution [7]. The standard procedure to measure smoothness applies a band-pass filter to the output signal of the potentiometer, and measures the maximum spike size produced when moving the wiper at a fixed speed over a set travel range. If the filter parameters and travel speed are standardized, smoothness measurements can be used to compare the performance of different potentiometers, but do not quantitatively measure resolution.

C. Hysteresis

Potentiometers can exhibit hysteresis due to friction between the wiper and track and compliance in the wiper. When the sensor approaches the same position from different

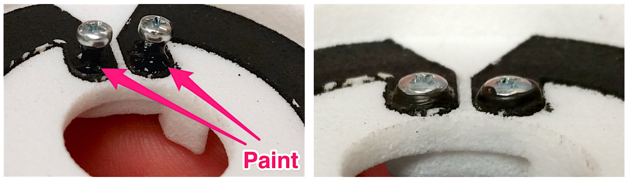

Fig. 2. A bead of conductive paint applied beneath the screw head forms a good electrical connection with the track.

directions, the actual position of the wiper on the strip (and therefore the output voltage) will be slightly different.

D. Lifetime

While there is no strict standard for potentiometer lifetime testing [9], accelerated lifetime testing typically involves repeatedly moving the potentiometer wiper through its full range until failure, and is reported in number of cycles.

IV. Design and Manufacturing

A. Design Overview

Referring to Figure 1, the distinguishing feature of a PaintPot is the resistive track surface, which is made of conductive spray paint. We use MG Chemicals Total Ground conductive paint [10], which is an off-the-shelf carbon-embedded spray paint easily applied by hand. Any non-conductive material can serve as track substrate. The paint adheres well to most plastics, making it possible to paint tracks directly onto existing parts by masking off a region with tape. Acrylonitrile butadiene styrene (ABS) plastic works particularly well, because the paint chemically etches the surface to form a durable resistive coating [10]. ABS sheet can also be cut to precise shapes in a laser cutter, allowing custom tracks to be precisely cut in a wide range of shapes and sizes.

Connecting electrical terminals to the painted surface can be difficult, because wires cannot be soldered and crimp connections would likely crack the painted surface. Good electrical terminals can be created by mounting zinc-coated screws at the ends of the resistive strip. As shown in Figure 2, conductive paint is applied beneath the screw heads before fully screwing them in. Leaded solder adheres to zinc-coated screws, allowing wires to be easily attached and detached.

The wiper can be chosen depending on the application. Wipers with high contact pressure should be avoided, as they may scratch the paint. Larger contact surface area also reduces contact resistance, improving signal quality. The Harwin S1791-42 EMI Shield Finger Contact serves as a good wiper for our PaintPots [11]. The wiper is a 4mm high gold-plated tin spring contact with a 1.45x2.05mm contact area, and a contact force of 1N (mounted at a 3mm working height).

B. PaintPots used in SMORES-EP

SMORES-EP (Fig. 3) is a modular robot with four actuated joints that require position sensing - three continuously rotating faces and one central hinge with a 180° range of motion [12]. The top, left, and right faces require power and data through a slip ring on the rotation axis, which complicates sensor positioning.

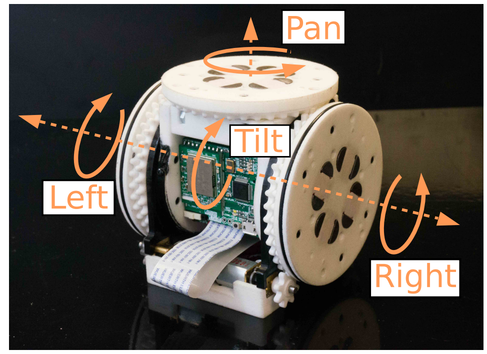

Fig. 3. SMORES-EP module with labeled joints. The module is the size of an $80mm$ cube.

Our decision to use PaintPots in SMORES-EP was driven by the tight space constraints inside the module. Absolute position sensing was necessary on all DoF. Optical track encoders were considered for the side wheels, but not enough space was available to fit multiple gray code tracks to measure tilt position. PaintPots proved to be a versatile, robust, and accurate solution.

1) Wheel PaintPots: The wheel PaintPots, shown in Figure 4, have a circular track and two wiper contacts. They allow continuous rotation and provide position information over the full 360^o range of the left, right, and pan joints. The annular geometry allows the slip ring to fit through the center. Tabs on the track extend into the center of the circle to provide space for the terminal contacts. The V-shaped gap provides enough space for the wipers to pass from one side of the track to the other without contacting both simultaneously (which would cause a short circuit).

The two wipers (Harwin S1791-42 [11]) are mounted on a PCB above the track, as shown in Figure 4. Using two wipers at a 50-degree angle to one another ensures that at least one wiper contacts the track even if one is in the gap, providing 360° of position sensing. To decide which wiper to use at a given time, we apply a simple rule. Angles are measured in the range $-\pi < \theta \leq \pi$, and since the two wipers are centered about the gap when $\theta = \pi$, we use one wiper if $\theta_{prev} < 0$ and the other wiper if $\theta_{prev} \geq 0$.

The track substrate is 0.79mm thick ABS sheet. To facilitate easy mounting, a layer of double-sided adhesive is applied to the back of the ABS sheet before cutting. Tracks are cut in batches in a laser cutter. After cutting, each track is gently sanded, removing plastic debris from laser ablation and providing an even rough surface ideal for paint adhesion, and then wiped with water to remove dust.

Tracks are hand-painted using spray cans of Total Ground conductive paint. Three coats of paint are applied, with five minutes of drying time between coats, following the painting guidelines in the datasheet [10]. Strips are allowed to dry for 24 hours before use, to ensure maximum durability. The total thickness of the sensor is $4.1mm$, including the adhesive layer, ABS sheet, paint, and wipers.

Strips are mounted in a mated groove in a 3D-printed chassis as shown in Figure 4. The chassis has a raised triangular feature that mates with the gap in the strip, so that

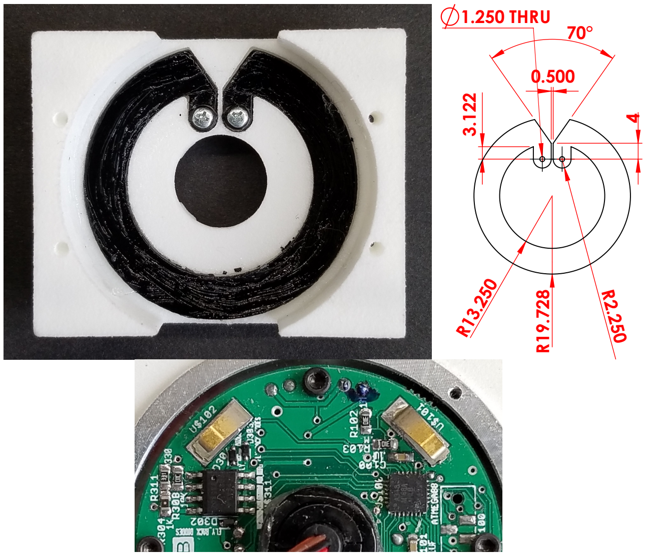

Fig. 4. Top Left: Wheel PaintPot installed in chassis. Top Right: Drawing of wheel PaintPot with dimensions in mm. Bottom: Circuit board used with wheel PaintPots showing Harwin S1791-42 wipers mounted at a 50° angle.

the wipers remains at the same level as they pass through the gap region. Zinc-coated screws ($m1.6$ x $6mm$) are used for electrical terminals, as described in Section IV-A. The measured terminal-to-terminal resistance of wheel PaintPots is between $2k\Omega$ and $20k\Omega$, depending on the thickness of the paint. Before use, a coat of petroleum-based grease is applied to the track surface.

2) Tilt PaintPots: The tilt PaintPots, shown in Figure 5, have resistive tracks with cylindrical curvature about their axis of rotation. A single wiper (Harwin S1791-42 [11]) contacts the track and measures position through the full $180°$ of motion of the tilt joint.

The track geometry of the tilt PaintPot makes very efficient use of space inside the SMORES-EP module. To our knowledge, no off-the-shelf potentiometers replicate this unusual non-planar shape. Some off-the-shelf slide pots can bend into curves [13], but come in predefined widths and lengths, making them difficult to mount in the module.

Tilt PaintPots have the same ABS/adhesive substrate as wheel PaintPots, and similar screw contacts. They are mounted to the 3D printed chassis before painting, allowing them to be painted in their final curved shape. This is preferable to painting flat and then bending: bending the paint after it has dried causes cracks to form, increases the resistance (three orders of magnitude) and causes a non-smooth variation of voltage along the length of the track. The terminal-to-terminal resistances of our tilt PaintPots fall between $3k\Omega$ and $10k\Omega$.

C. Cost

PaintPots are inexpensive. At the time of writing, the most expensive components in the SMORES-EP wheel and tilt PaintPots are the Harwin S1791-42 wipers, available from Digikey.com for $0.35 USD in quantities of 100. MG Chemicals Total Ground spray paint can be purchased from Amazon.com for $16 USD, and 0.79mm ABS sheet can be purchased from McMaster.com for $3.70 USD per square foot. Based on these prices, materials for our wheel PaintPots cost $1.05 USD, and tilt PaintPots cost $0.70 USD (including material wasted during manufacturing). After quality control testing (described in Section VI), we yield about 75% of our wheel PaintPots and 90% of our tilt PaintPots, making the effective materials costs $1.40 USD and $0.78 USD, respectively.

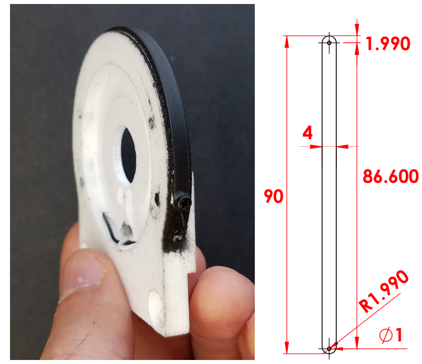

Fig. 5. Top: Tilt PaintPot installed on chassis with cylindrical curvature (28.5mm radius). Bottom: Drawing of tilt PaintPot track (laid flat) with dimensions in mm.

V. Calibration

As discussed in Section II, potentiometers are typically modeled as linear. Close adherence to the linear model is achieved by ensuring that resistivity is constant along the track, which involves ensuring uniform geometry, thickness, and material properties of the track. This requires careful quality control, which is expensive.

As an alternative, a calibration process can be used to achieve good performance. Our PaintPots are manufactured using a low-cost process (hand spray painting) without significant process control, and are somewhat nonlinear. By relying on a calibration process, we effectively trade manufacturing cost for additional computation, and achieve performance comparable to off-the-shelf potentiometers of greater cost.

A. Ground-Truth Data: AprilTags

AprilTags are an open-source, inexpensive, marker-based motion capture system, requiring only a camera, paper tags, and open-source software [14]. Unlike many position measurement devices (like shaft encoders), they do not require mechanical fixturing: tracking two rigid bodies (PaintPot track and wiper) only requires attaching paper tags to each body. Mechanical fixturing is particularly difficult for SMORES-EP modules, which have five independently moving rigid bodies.

During calibration, a PaintPot is moved through its entire range of motion ($360°$ for wheel, $180°$ for tilt) in both directions, while voltage and ground-truth angle data are recorded. The data rate is limited by the speed of the AprilTag software, which runs at about 12hz. Calibration takes about 50 seconds, during which about 600 datapoints are gathered.

B. Model fitting

While the voltage data from our PaintPots is often nonlinear, it does tend to be smooth and monotonic. As a result, the first order (linear) model typically used to model potentiometers is insufficient, but a significantly more complex model is not necessary to capture the variance. We found that a third-order polynomial ($X_w = a_3V_w^3 + a_2V_w^2 + a_1V_w + a_0$) provides a suitable model. In addition to good prediction performance (discussed in Section VI-A), third-order polynomials can be accurately and quickly computed with the floating-point unit on the SMORES-EP microcontroller (STM32f303).

While third-order polynomials provided good performance for our applications, alternative models (such as piecewise linear interpolation) could also be explored.

VI. Performance

A. Accuracy

Given an N-sample dataset consisting of estimated angles $\hat{\Theta} = \left\{\hat{\theta}_1, \hat{\theta}_2, \ldots, \hat{\theta}_N\right\}$ and ground truth angles $\Theta = \{\theta_1, \theta_2, \ldots, \theta_N\}$, define the *error* to be $E = \left\{e_i = \theta_i - \hat{\theta}_i \;\forall\; i \in [1, N]\right\}$. We compute three error metrics for each dataset. *Root-mean-squared (RMS)* error is a measure of average error magnitude over the entire dataset, computed: $E_{RMS} = \sqrt{\sum_{i=1}^{N} e_i^2}$. *Median error* E_{med} is the median of all e_i. *Maximum error* E_{max} is the maximum error magnitude after applying a median filter (with window size 3) to remove electrical noise, $E_{max} = \max_i |\mathrm{medfilt}(e_i)|$.

These error metrics are listed in Table I for a population of 11 wheel PaintPots and 16 tilt PaintPots. Conformity values are computed by dividing the maximum error by the angular travel range for each PaintPot (360° for the wheel, 180° for tilt). The conformity values for tilt and wheel PaintPots are 2.68% and 2.14% respectively, making them competitive with off-the-shelf potentiometers of similar cost. Section VI-E provides a comparison with commercial potentiometers.

To guarantee consistent performance, every PaintPot used in SMORES-EP is evaluated during calibration. Any PaintPot with $E_{RMS} \geq 6.5°$, $E_{med} \geq 2°$, or $E_{max} \geq 20°$ is considered out-of-spec, and is discarded (Estimated to be 25% of wheel tracks and 10% of tilt tracks).

TABLE I

Error metrics for PaintPots

	Tilt PaintPot	Wheel PaintPot
RMS	$1.96° \pm 0.10°$	$2.92° \pm 1.39°$
Median	$-0.10° \pm 0.28°$	$0.06° \pm 0.29°$
Max	$4.83° \pm 2.25°$	$7.70° \pm 3.56°$
Conformity	$\mathbf{2.68\% \pm 1.25\%}$	$\mathbf{2.14\%° \pm 1.0\%}$

B. Resolution

The resolution limit of our potentiometers was obtained using the experimental setup shown in Figure 7. It consists of an 80mm long slide PaintPot with the wiper mounted on a linear stage whose position is controlled by a servo-driven micrometer. The PaintPot is configured as a voltage divider, with terminal voltages of 0V and 12V.

Four datasets were gathered with the servo turning at a constant rate of 0.066 revolutions per second, corresponding

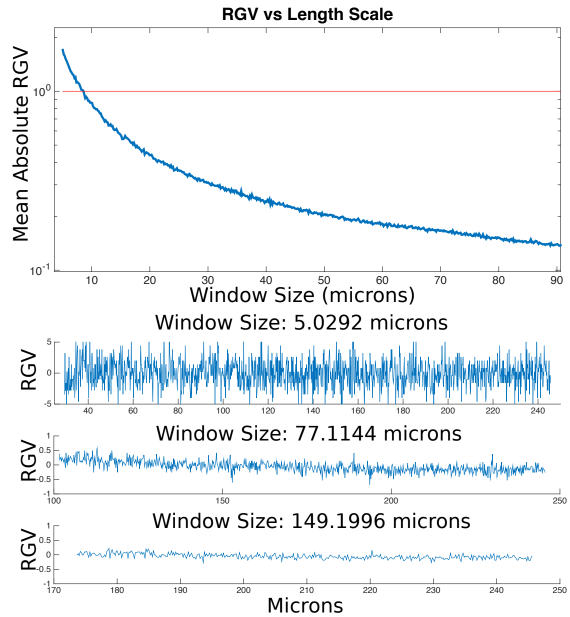

Fig. 6. Top: Plot of mean absolute RGV with increasing window size. Red line indicates resolution limit, $\overline{|RGV|}(w) = 1$. Right: Bottom of RGV computed on the same dataset with different window sizes. We can see that the data becomes smoother with increasing window size.

to a wiper travel rate of $41.91\mu m$ per second. Data was gathered for approximately 5 seconds, for a total travel distance of about $200\mu m$. All four datasets traverse the same region of the strip. Voltage was sampled with an oscilloscope range of 40mV at a rate of 0.004s, corresponding to a travel distance of $0.168\mu m$ per sample. $\overline{|RGV|}(w)$ was computed for each dataset using window sizes ranging from 30 samples ($5.03\mu m$) to the length of the entire dataset in increments of 1 sample (Figure 6). Results from all four datasets agree closely. Averaging over all datasets, we compute $w_{res} = 8.63\mu m$, with a standard deviation of $0.216\mu m$ (3%). For reference, some high-precision potentiometers from Novotechnik have $w_{res} = 1.5$ to $3.5\mu m$ [15].

The small resolution limit of PaintPots means that the properties of the wiper and track will not be the limiting factor in precision for many applications. In SMORES-EP, the limiting factor is the ADC bit depth (10 bits, or $84\mu m$ for the 86.6mm long tilt PaintPot). To reach the material resolution limit, 14 bits of ADC depth would be required.

C. Hysteresis

PaintPot hysteresis was measured using the same experimental setup for RGV shown in Figure 7. To test hysteresis, the wiper was set to an initial position using the micrometer. The oscilloscope ground bias voltage was then adjusted to bring the measured wiper voltage as close as possible to zero, allowing the voltage scaling to be set as small as possible.

The wiper was then moved to the right 6.3mm, moved back to the zero point, and allowed to sit for two seconds before voltage was recorded. The procedure was then repeated, moving the wiper to the left instead of the right. The entire procedure was repeated 10 times. Five such experiments were conducted at five different initial positions on the strip. The hysteresis voltage is: $V_h = \frac{1}{2}|V_L - V_R|$ where V_L and

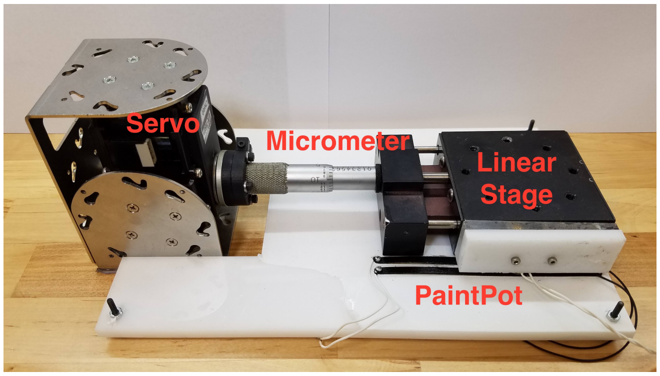

Fig. 7. Testing setup used to evaluate RGV and hysteresis.

V_R are the voltages after moving left and right during a trial.

The average hysteresis voltage over 30 total trials was $0.49mV$ with a standard deviation of $0.34mV$ (70%). Converting to an equivalent distance (by multiplying by the average slope $\frac{\Delta V}{\Delta X}$), we find a hysteresis distance of $10.1\mu m$, with a standard deviation of $7.1\mu m$. Like the resolution limit, the small hysteresis of this wiper and track is unlikely to be the limiting factor in overall precision for many applications.

D. Lifetime

While PaintPots are not intended to be long-life sensors for industrial purposes, adequately long lifetime is required for even low-cost applications. Wheel PaintPot lifetimes were evaluated by fixing a DC gear motor to the outside of a SMORES-EP face, spinning at 167 RPM. Every hour (after 10,020 revolutions), data is collected and evaluated according to the criteria presented in Section V to determine if the PaintPot still meets our minimum standards for use.

TABLE II

TRACK LIFETIMES

#	Cycles (x1000)	Group	Failure mode
1	380	A	Wear through
2	190	A	Wear through
3	60	B	Local Pitting
4	50	B	Local Pitting
5	40	B	Local Pitting
6	20	C	Local Chipping
7	10	C	Local Chipping

Table II shows lifetime tests from seven wheel PaintPots. Tracks from group A have three layers of paint, and were hand painted in small batches (1×4 grid of tracks), allowing the painter to carefully control the thickness of each layer of paint. Tracks in group B were painted in large batches (4×9 grid), making it more difficult to control paint quality. When tracks from group B failed, it was due to visible pitting in the top layer of paint. When the wiper hits these pits, the signal becomes noisy, and falls outside the acceptable bounds for maximum error. Tracks from group A were much more durable, lasting hundreds of thousands of cycles, and typically exhibiting an even wear pattern over the track.

In light of these results and our experience with the painting process, we hypothesize that group B had regions of thick paint that are not well bonded to the ABS surface, creating "soft spots" that wear away more easily. This hypothesis is further supported by the results from group C, which were painted with five coats of paint rather than three. Both tracks from group C failed when paint chipped off the track after a relatively small number of cycles. Based on these experiments, we recommend using a maximum of three coats of paint, and taking care to apply paint evenly.

Lubrication can also contribute to the longevity of PaintPots. Without lubrication, wheel PaintPots can fail at under 10,000 cycles. Silicone-based dielectric grease and petroleum jelly lubricants were found to be equally effective. Tracks tested in Table II were lubricated with petroleum jelly.

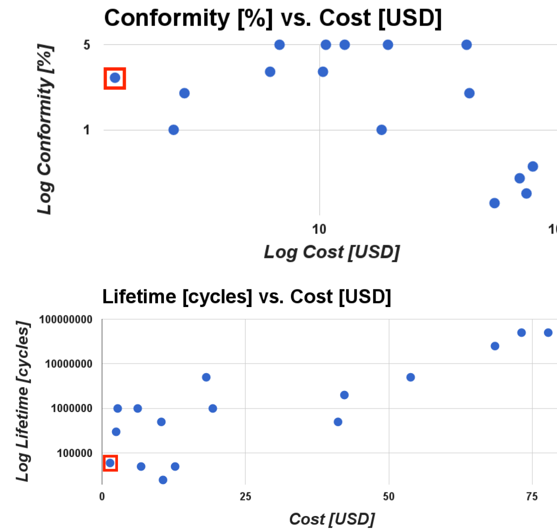

Fig. 8. Plots of cost vs. conformity and cost vs. lifetime for commercial potentiometers with features similar to the wheel PaintPot (360° sensing range and continuous rotation). PaintPot marked with red square.

E. Comparison to Commercial Potentiometers

PaintPots can be tailored to the needs of an application at a cost of around $1 USD, while achieving performance of more expensive potentiometers with similar features. Figure 8 plots cost versus linearity for 20 potentiometer position sensors with features similar to our wheel PaintPot (continuous rotation and 360^o sensing range). The wheel PaintPot (red square) offers good conformity at a lower cost than the majority of available potentiometers. Its disadvantage is a shorter lifetime, which in many robotics applications is not a major concern. In the case of SMORES-EP, none of these other potentiometers had a form factor that could meet the other design requirements (such as a through-hole large enough for the slip ring in the middle of the face).

When considering cost and conformity, it is important to note that PaintPots rely on a calibration function, which requires additional computation. The calibration process presented here could be used with other potentiometers to increase performance, but in essence demonstrates the computation for cost trade-off.

VII. TWO-DIMENSIONAL PAINTPOTS

The customizability of PaintPots enables many interesting sensing modalities. A spherical PaintPot is created by painting a plastic sphere (Figure 9), and can be used to sense

Fig. 9. Left: Spherical PaintPot that senses position on the top hemisphere. Right: Flat-sheet PaintPot capable of sensing the X-Y position of the wiper.

the position of a wiper on its top half. The sensor has four terminals as shown in Figure 10. Position sensing is done in two alternating steps. In step 1, terminals A0 and A+ are held at ground and 3.3V respectively, while B0 and B+ are left floating. This creates a voltage field that varies linearly with arc length from A0. By reading the voltage, the wiper is localized to a circle on the surface. In step 2, B0 and B+ are held at ground and 3.3V while A0 and A+ are left floating, localizing the wiper to a different circle. The position of the wiper is the intersection of the two circles within the top hemisphere. If a third pair of electrodes were used, the wiper could be localized on the entire sphere.

A flat-sheet PaintPot (Figure 9) uses a similar method to determine the X-Y position of the wiper. Four contacts positioned at the corners of the sheet are alternately activated and deactivated in a similar way to the sphere (Figure 10). Each sensing step localizes the wiper to a horizontal or vertical line. For a simple cartesian mapping from voltage to position, ideally two full sides of the rectangle would be held at known voltages. However, wiring the entire side would create short-circuits at the corners. Instead, two points along each side are used, which creates nearly-even voltage field lines in the middle of the sheet.

The 2D sheet PaintPot can be used as a touchpad to capture writing, as demonstrated in the accompanying video. The surfaces are durable enough that the stylus (a multimeter probe) does not scratch them under normal writing pressure. The sphere and sheet PaintPot each cost about $1 USD to make. The performance of these 2D PaintPots could be improved through calibration. Similarly to the procedure employed for the 1D PaintPots, the sheet or sphere could be calibrated by measuring voltages at known coordinates on the surface, and fitting a parametric function for each coordinate as a function of the two measured voltages.

VIII. Conclusion

We presented a method to create custom potentiometers for position sensing at low cost. The manufacturing process uses widely accessible materials, requires no special expertise, and can create potentiometers in a variety of shapes and sizes, including curved surfaces. This enables designers to integrate custom sensors into their designs, even if they would not normally have the expertise or funding to do so.

Our calibration process is low-cost and adaptable. Once calibrated, PaintPots offer accuracy and precision on par with commercial potentiometers of comparable cost. We believe this makes them a competitive alternative to off-the-shelf potentiometers, even in high-performance applications.

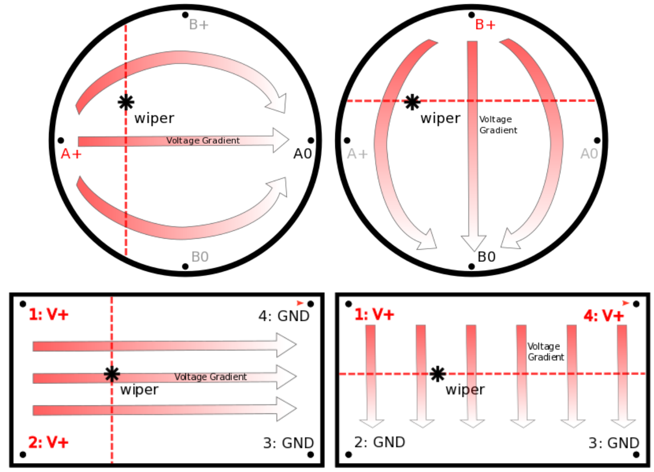

Fig. 10. Top: Top-down view of voltage gradients on the sphere PaintPot. Bottom: Voltage gradients on sheet PaintPot.

PaintPots are not without disadvantages. The tracks have shorter lifetimes than commercial potentiometers. Wiper alignment is important: if a wiper contacts the track on its corner or edge, the pressure concentration can scratch the painted surface. Calibration allows good accuracy at low cost, but requires time during manufacturing, and more complex software. Time must also be spent identifying tracks that are up-to-spec for high-performance applications.

In the future, well-established automated painting processes could greatly improve PaintPot consistency over hand-painting. While hard metal wipers proved the best choice for the SMORES-EP PaintPots (because of their low profile and low hysteresis), other types of wipers might be optimal for other applications. In particular, softer brush-type wipers might afford longer lifetimes.

References

[1] A. Mehta *et al.*, "Cogeneration of mechanical, electrical, and software designs for printable robots from structural specifications," in *IROS*, 2014.

[2] S. Miyashita *et al.*, "An untethered miniature origami robot that self-folds, walks, swims, and degrades," in *ICRA*, IEEE, 2015.

[3] *Sensoink Technical Specifications*, 2016. `www.sensoink.com`.

[4] S. Miyashita *et al.*, "Self-folding printable elastic electric devices: Resistor, capacitor, and inductor," in *ICRA*, IEEE, 2014.

[5] Y. Kawahara *et al.*, "Instant inkjet circuits: lab-based inkjet printing to support rapid prototyping of ubicomp devices," in *ACM conference on Pervasive and Ubiquitous computing*, pp. 363–372, ACM, 2013.

[6] S. Olberding *et al.*, "A cuttable multi-touch sensor," in *ACM Symposium on User Interface Software and Technology*, pp. 245–254, 2013.

[7] Variable Electronic Components Institute, *Industry Standard Wirewound and Nonwirewound Precision Potentiometers*, 1988. Rev. A.

[8] *Measurement Systems Analysis*. Chrysler Corp., 2010.

[9] "Potentiometers." `www.novotechnik.de/en/products/sensor-technologies/potentiometers`. Accessed: 8/1/16.

[10] MG Chemicals, *Total Ground Carbon Conductive Coating 838 Technical Data Sheet*, January 2013. Ver. 1.04.

[11] Harwin Inc, *S1791-42R Customer Information Sheet*, 2016.

[12] T. Tosun, J. Davey, C. Liu, and M. Yim, "Design and characterization of the ep-face connector," in *IROS*, IEEE, 2016.

[13] *Membrane Potentiometer*, 2016. `www.spectrasymbol.com`.

[14] E. Olson, "Apriltag: A robust and flexible visual fiducial system," in *ICRA*, pp. 3400–3407, IEEE, 2011.

[15] Novotechnik Siedle Group, *Series PRS Resistance Elements*, 2016. `http://www.novotechnik.com/pdfs/PRS_e.pdf`.