Proceedings in Manufacturing Systems, Volume 11, Issue 4, 2016, 201-206 ISSN 2067-9238

ADDITIVE MANUFACTURING INTEGRATION OF THERMOPLASTIC CONDUCTIVE MATERIALS IN INTELLIGENT ROBOTIC END EFFECTOR SYSTEMS

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Abstract: *With multiple improvements in the field of control systems, sensors and image processing systems, the applicability of robots is expanding to new areas previously served by human labor such as harvesting fruit and vegetables. For these new areas, new and improved end-effector systems are also needed, as the objects which require handling have diverse dimensional properties, complex surfaces, varying degrees of softness. These new application areas demand intelligent features such as touch sensing, gripping force sensing and accurate position sensing. In the past few years, additive manufacturing has shifted from rapid prototyping to printing functional parts. Latest polymer material advances for fused filament fabrication enable printing parts with various properties, including electric current conductivity. In this paper, the authors are looking at the novel possibility of integrating these new conductive materials into simple, yet intelligent end-effector systems. Several principles have been investigated and analyzed for their usefulness. The authors have fabricated parts with fused filament fabrication which integrate force-sensitive electromechanical switches, capacitive sensing or bend sensors for determining finger position in adaptive grippers. The parts, 3D printed from commercially available filaments, have been subjected to various tests which demonstrate promising results and potential applicability in real-life applications.*

Key words: *adaptive grippers, additive manufacturing, integrated sensing, capacitive touch.*

1. INTRODUCTION

Following the improvements in the field of control systems, sensors and image processing systems used in robotics, the capabilities of robots also increase. Thus, we are witnessing a continuous expansion of the fields where robotic systems can be implemented in order to replace human workforce.

New applications for robotic systems, such as harvesting fruits and vegetables in agriculture, and also improvement of existing capabilities in industrial settings, such as the capacity to pick up objects with different geometries placed within the workspace of the same robot, demand new developments in the field of robotic end-effectors.

For this purpose it is useful to develop intelligent or adaptive end-effector systems, which can use data taken from the environment in order to adapt to a larger number of situations, compared to common end-effectors which are designed to work for a single type of object and geometry.

Large corporations active in the field of industrial automation, along with university laboratories across the world have researched and developed a diverse number of solutions to deal with these emerging problems. Evologics GmbH developed the adaptive geometry named Fin Ray, which is based on the mechanisms observable in fish fins [1]. This geometry has a large advantage over serial or parallel cinematic chains by being capable to adapt around a curved surface. Based on the Fin Ray geometry, Festo AG developed products such as MultiChoiceGripper, a pneumatic adaptive gripper with 3 fingers which can reposition its fingers to pick up cylindrical or spherical objects [2].

Other approaches include making actuators using the principle of electro-adhesion applied on a polymer base [3] or the use of dielectric elastomers to make an actuator which can roll around objects [4].

Additive manufacturing, a process of making objects by adding successive layers of material onto a base layer offers the possibility of creating mechanical components with properties that are suitable to fulfill these new challenges faced by robotic end-effectors. Fused deposition modeling [5] is an additive manufacturing process which uses extruded thermoplastic filament to create layers of material. Because the thermoplastic material is first extruded into a filament, other materials can be integrated by adding other materials in the mix. By integrating fillers such as metallic powders [6], carbon powders, carbon nanotubes [7], wood fiber [8], etc. in the thermoplastic filament, the final printed parts can retain some of the filler's physical and chemical properties. By integrating carbon powder or graphene into an acrylonitrile-butadiene-styrene (ABS), polylactic acid (PLA), polycaprolactone (PCL) or thermoplastic polyurethane (TPU) base, researchers have developed filament that can conduct electrical current [9].

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This type of filament has made its way into several research programs. PrintPut is a project that aims for developing a touch sensitive user interface that can be applied on complex surfaces and it is one of the possible real-world applications of 3D printed conductive materials.

In this paper the authors are looking at combining these advances in 3D printing materials with the advances in robotic end-effectors by analyzing the possibility of integrating thermoplastic materials with conductive properties into end-effector finger design in order to create intelligent end-effector systems.

2. METHOD AND PRINCIPLES

From the perspective of using data from the environment using conductive materials, several mechanical or electrical principles that could be exploited and integrated into a robotic end-effector have been identified and considered for testing. Fused Filament Fabrication (FFF) additive manufacturing is a process largely based on thermoplastic polymers. When combined with conductive properties, the elastic properties of these polymers can be used to design electromechanical systems such as electromechanical switches, resistive touch sensors or bend sensors.

Thermoplastic materials with conductive properties can be 3D printed into electrical circuits. These electrical circuits can be formed into resistive touch and pressure sensitive surfaces [10]. The same circuit can be formed to provide multiple touch-sensitive areas.

Another electrical principle of interest is capacitive sensing. By putting a layer of conductive material onto an insulating layer a capacitor can be formed where the conductive layer is its electrode. By touching this electrode, the capacitance of the system is modified through interfering with its electrostatic field. The capacitive method is largely used where touch sensing is needed, but can also be adapted for pressure sensitive applications [11].

2.1. End-effector fingers with integrated electromechanical switches for force-sensitive gripping.

An area of large interest is the manipulation of sensitive objects, which require either deformable end-effector systems or end-effectors with force-sensing capabilities. To tackle this issue, the authors are presenting a finger for use in robotic end-effector systems which has an integrated force sensitive switch (Fig. 1,*c*).

The authors intend to demonstrate that 3D printing can be used to fabricate force-sensitive end-effector fingers by using conductive thermoplastic material. The finger is fabricated through FFF additive manufacturing using a dual extruder 3D printer. Embedded in the PETG base structure is a structure made out of conductive thermoplastic material with elastic properties PI-ETPU 95–250 produced by Palmiga Innovations. This conductive material, once printed, has a Shore A hardness of 95 (ISO 868) and a volume resistivity of less than 1 Ωm. The elastic properties of the material are exploited to create a force-sensible end-effector finger by printing 2 layers of conductive material separated by a distance *d*. Upon the gripping force being applied by the finger on the target object, the first layer of material suffers elastic deformation until it comes into contact with the second layer and closes the electrical circuit.

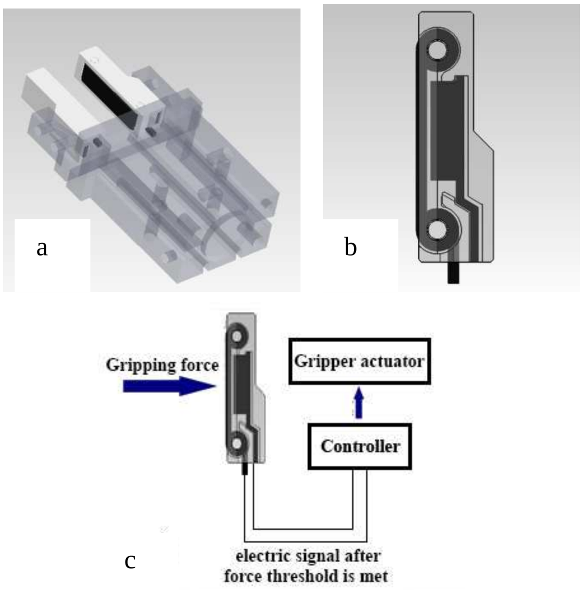


Fig. 1. *a* – 3D model of gripper with 3D printed finger; *b* – 3D model of finger with integrated electromechanical switch; *c* – working principle of 3D printed force-sensitive finger.

Thermoplastic polyurethane is known for exhibiting nonlinear hyperelastic behavior, high rate dependency, high hysteresis and it softens with cyclic loading depending on the maximum strain level reached in prior cycles [12]. The design of the gripper finger is made to accommodate these facts and keep maximum strain level to a minimum. During operation, the strain level is kept under 10% of the maximum allowed strain.

The models used for testing where made with conductive layers with a thickness of 2.5 mm and an unsupported length of 35 mm. 5 testing samples were made, with a distance between conductive layers which varies in 0.25 mm increments, starting at 0.5 mm (Fig. 2,*a*).

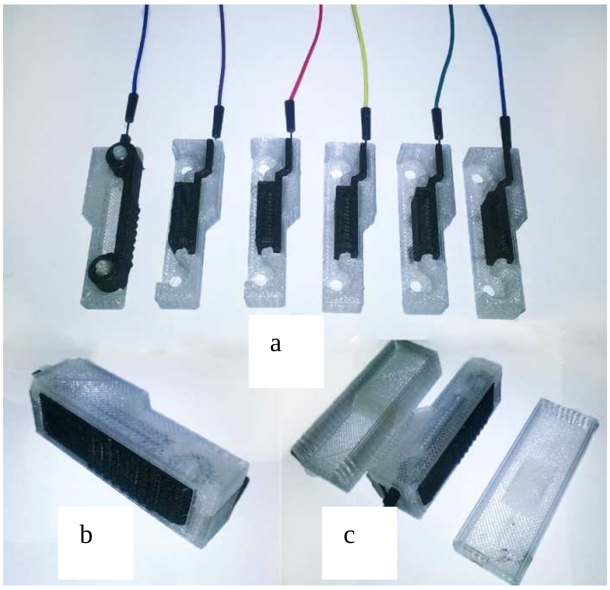


Fig. 2. Finger with embedded electromechanical switch: *a* – 3D printed testing samples with varying distance between conductive layers; *b* – assembled 3D printed finger; *c* – finger with testing guide.

For use during testing, a guide which will simulate the finger coming into contact with a cylindrical object 30 mm in diameter was designed and 3D printed (Fig. 2,*b*). For ease of the testing process, the parts were printed separately and assembled afterwards, but the geometry allows for printing as a single piece.

2.2. End-effector fingers with integrated capacitive touch sensing.

The ability to sense contact between an end-effector's fingers and a target object is important, especially when it comes to the manipulation of soft objects [13].

The second model which was designed and analyzed uses capacitive sensing to detect the contact of the end-effector finger with certain objects (Fig. 3). The conductive layer (electrode) of the capacitive sensor is made out of an ABS polymer which contains carbon powder filler and the insulating layer is made out of polyethylene terephthalate glycol-modified (PETG) polymer.

A test part with the same dimensions as the ones in the previous experiment was designed and fabricated (Fig. 4).

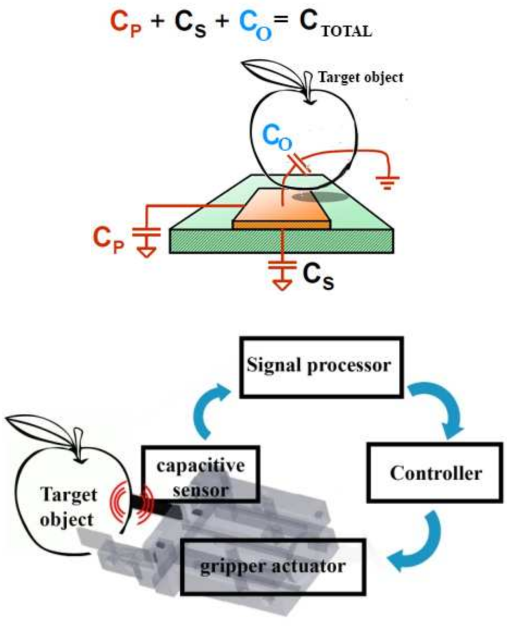


Fig. 3. Working principle of end-effector with capacitive sensing capabilities.

Fig. 4. 3D printed end-effector finger with capacitive touch sensing.

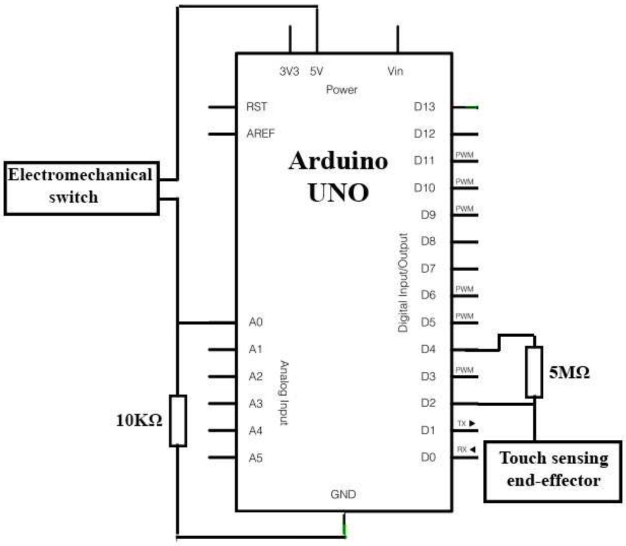


Fig. 5. Testing circuits (on the left side of the Arduino board for testing the electromechanical switch and the adaptive Fin Ray finger; on the right side, for testing the touch sensitive capacitive end-effector finger).

The capacitive response of the part was tested by connecting it to an Arduino Uno with the CapSense library. A signal is sent from one of the Arduino pins through the part and into a receive pin. The send and receive pins are connected through a 5 MΩ resistor (Fig. 5).

When the send pin changes state, it triggers a delayed change of state of the receive pin. The delay between the send pin changing state and the receive pin changing state is determined by a time constant defined by $R \cdot C$, where R is the value of the resistor and C is the capacitance at the receive pin plus any other capacitance present at the receive pin, which acts as a sensor (Fig. 3,*a*). In applications where numeric values of capacitance are of interest, a small capacitor, the order of 10^2 pF is needed in parallel with the target object to stabilize delay readings. However, since interest is only in observing the delay in arbitrary units, not in the numeric values, no other capacitor added in parallel to the detected object is needed.

This sensing method works with any object that is conductive or that has a dielectric different from air so it is of interest in applications such as picking up fruits and vegetables or metal objects such as aluminium cans.

The 3D printed test part is tested by connecting it to the test circuit and bringing it in contact repeatedly with several objects, such as tomato, lemon, apple, bell pepper, pomegranate, bread, aluminium can.

In order to verify the model's applicability in real life scenarios, different testing routines were analyzed: in the first routine, a pick & place routine is simulated by touching the target object with the gripper finger for 3 seconds, then releasing it for another 3 seconds(Fig. 10,*a*). In the second routine, a medium length grip on the target object that lasts 10 seconds is simulated (Fig, 10,*b*), and in the last routine a longer grip of 30 seconds (Fig. 10,*c*) is simulated. Testing was conducted at room temperature of 24 °C.

2.3. Fin Ray Effect gripper finger with integrated bend sensors

End-effectors using the Fin Ray Effect are used in applications where adaptability to cylindrical, spherical or complex surfaces is needed [14]. When integrated into electric end-effectors, certain properties such as gripping force, pressure on the target object or estimated finger position can be determined by analyzing the stall characteristics of DC electric motors [15]. However, with pneumatic-actuated grippers and with non-parallel or series kinematics such as with the Fin Ray Effect geometry, these properties are harder to determine.

Also, an accurate determination of the finger's position is not possible without the use of sensors, mainly imaging sensors, because such an end-effector does not have serial or parallel kinematic chain.

Considering that Fin Ray Effect fingers used in end-effectors can be fabricated using 3D printing, the possibility of integrating conductive material filaments to form integrated sensors in such end-effector fingers should be analyzed. One such example is integrating a bending sensor into a Fin Ray finger with the use of a dual extruder printer (Fig. 6).

The base structure was fabricated from unfilled ABS polymer while the conductive circuit was made from ABS filled with carbon particles.

The conductive circuit has a total length of 160 mm and a cross-section area of 3 mm^2. The resistivity of the conductive filament was measured prior to printing and it amounts to $5 \cdot 10^3$ Ωm.

In order to show this model has potential in determining the finger position during gripping, the resistivity of the conductive circuit during idle and during bending under load will be measured. By showing that there is a proportional correlation between an applied force which causes the finger to deform elastically and the resistance of the integrated conductive circuit, a case could be made that the solution is suitable for determining the position of the finger. This fact is tested using the same experimental setup as in the first studied model. The setup consists in a rectangular steel bar with known dimensions which is elastically deformed by applying force with the end-effector finger. The deformation of the bar is read using a mechanical comparator and the resistance of the integrated conductive circuits is read using an ohmmeter (Fig, 7). A guide that is meant to keep the adaptive end-effector finger with one of its sides in vertical position while testing was designed and 3D printed (Fig. 8).

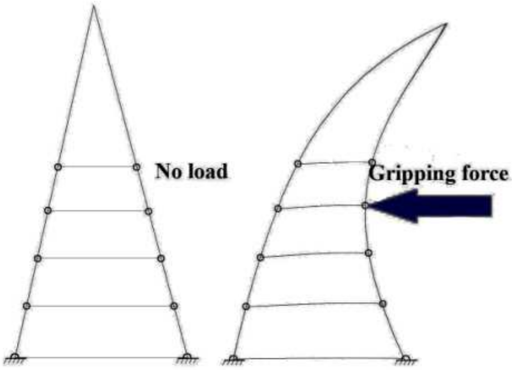


Fig. 6. Working principle of Fin Ray Effect end-effector fingers.

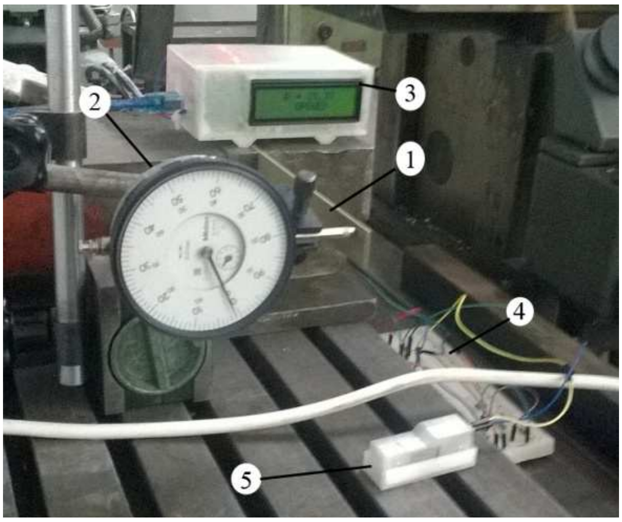


Fig. 7. Experimental setup for measuring force and resistance: 1 – steel bar; 2 – mechanical comparator; 3 – ohmmeter; 4 – test circuit; 5 – end-effector finger.

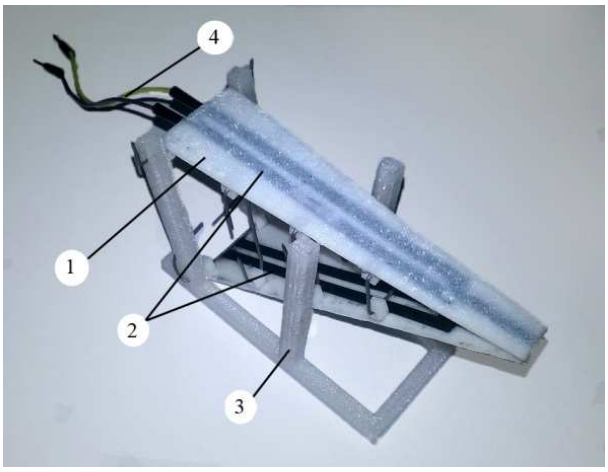


Fig. 8. 3D printed adaptive finger with integrated bending sensor: 1 – adaptive finger; 2 – integrated conductive circuit; 3 – support structure; 4 – wires.

3. RESULTS AND DISCUSSION

A. Testing the end-effector finger with integrated force-sensitive electromechanical switch gave promising results in terms of repeatability and design flexibility. As it can be seen in Fig. 9, the force needed to trigger the electromechanical switch is accurate within 1-sigma.

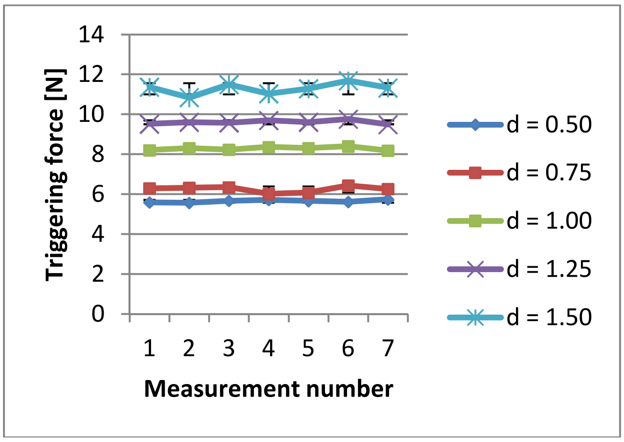
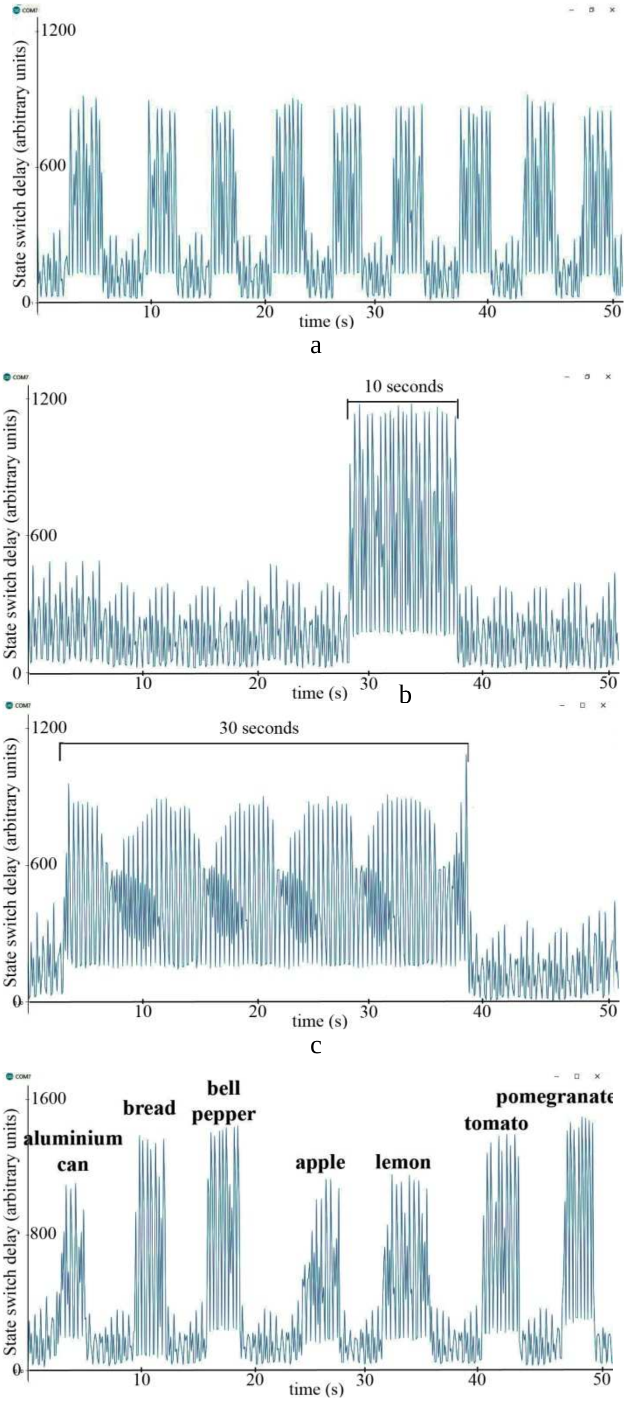


Fig. 9. Trigger force measurements for the electromechanical switches.

B. Testing the touch sensitive end-effector finger produced good and reliable results, showing potential for applicability in real-use scenarios. Discounting the ripple effect caused by the absence of a known capacitor in the testing circuit, as mentioned previously, it can be observed that the measurements are stable in time, both for short-timed, repeated gripping sequences (Fig. 10,*a*), as well as for longer contact periods (Figs. 10,*b* and 10,*c*).

Because the thermoplastic conductive material has high electrical resistance, the resistance of 5 MΩ needed for the part to function as a capacitive touch sensor can be replaced by integrating a secondary 3D printed conductive circuit inside the end-effector finger. This would simplify the external electric circuit needed to run the capacitive sensor and reduce cost with manufacturing and assembly.



a

b

c

d

Fig. 10. Graphed results of capacitive touch test: *a* – repetitive test of finger contact with a tomato; *b* – 10 seconds gripping simulation of a tomato; *c* – 30 seconds gripping simulation of a tomato; *d* – various objects tested.

The electrical resistivity ρ is defined as:

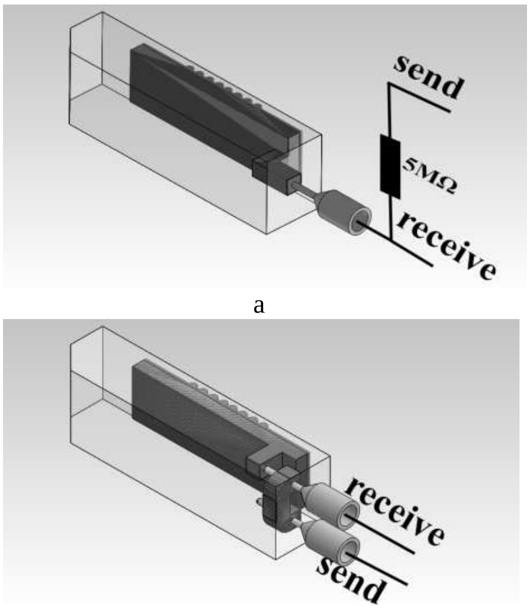
$$\rho = R\frac{A}{l}, \tag{1}$$

where *R* is the electrical resistance of a uniform specimen of the material; *l* – length of the piece of material; A – cross-sectional area of the specimen.

Previously, the resistivity of the conductive filament was measured to be $5 \cdot 10^3$ Ωm. From this, it can be calculated that the length of a conductive part with a section of 9 mm^2 needed to replace the 5 MΩ resistance is 9 mm. It should be noted that, depending on the size of the resistor needed, it might not be possible to fabricate the conductive circuit without increasing the volume of the part or without weakening the mechanical structure of the part.

Figure 11 shows a parallel view between the 3D model of the part previously tested and the 3D model of this new design.

C. Upon testing the adaptive finger, an inverse correlation between applied force, meaning the resulting deformation of the end-effector finger, and the electric resistance of the integrated conductive circuit is easily observable (Fig. 12).



a

b

Fig. 11. Comparison: *a* – tested model (top); b – proposed model with integrated resistance (bottom).

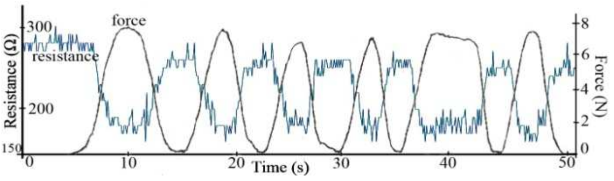


Fig. 12. Testing of the adaptive end-effector finger with integrated bending sensors.

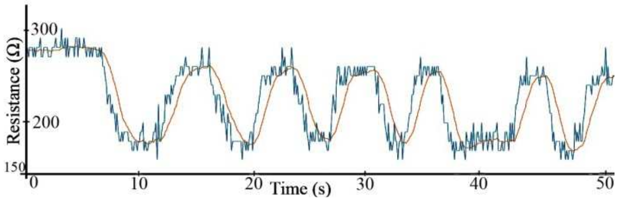


Fig. 13. A 15-period moving average smoothing algorithm applied to the measured effect.

In order to eliminate measurement variance, a simple smoothing algorithm can be used. The effect of an unweighted sliding-average smoothing algorithm is represented in Fig. 13.

This approach comes with the downside of losing some of the responsiveness of the sensing system, as the measured effect is delayed by a period equal to the timeframe over which the smoothing algorithm is considered. Depending on application, this delay may or may not be relevant.

To help reduce this delay while maintaining the smoothing factor, faster sampling is one of the potential solutions.

4. CONCLUSIONS AND FUTURE RESEARCH

In this paper, the authors have provided proof of concept that conductive thermoplastic materials can be successfully integrated in additive manufactured parts with the goal of creating end-effectors with sensing capabilities. The novel 3D printed electromechanical switch, capacitive touch sensing finger and adaptive finger with integrated bending sensors are models which open a path to create novel intelligent end-effector systems which require less costly manufacturing and assembly. To function, the proposed models require simple electronics found in common robotic controllers, which means that the solutions could be implemented with little or no extra cost. Taking this into consideration, a technology roadmap could be envisioned (Fig. 14).

Future research will focus on solving the challenges that have been identified, such as the need for robust signal processing, as well as on verifying the suitability of operating in real life environment. Also, future models that integrate multiple capabilities presented in this paper are to be designed and tested. Of particular interest is the integration of touch and force sensing capabilities in adaptive end-effector fingers. This would allow the replacement of the usual complex and expensive imaging systems that are used for sensing. The capabilities addressed in this paper are not exhaustive and other capabilities are also to be discussed and researched.

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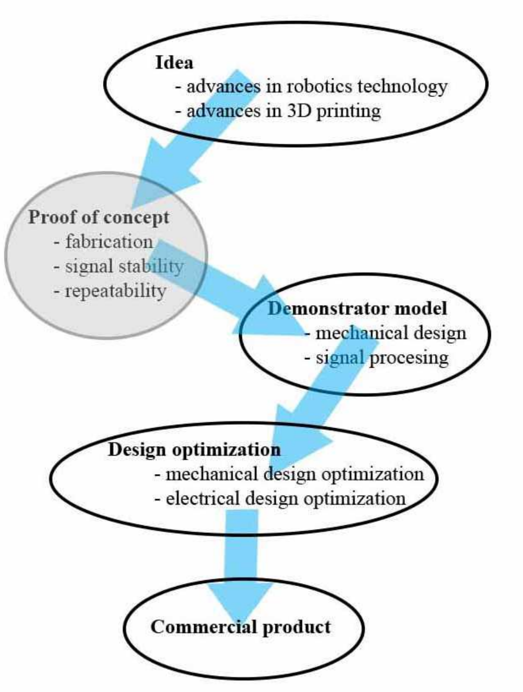

Fig. 14. Envisioned technology roadmap.

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