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Mechatronic Finger Structure with Pressure-Sensitive Conductive Layer

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Abstract. In this paper a unified approach of a mechatronic hand enriched with a pressure sensitive layer is analyzed. New developments of advanced applications regarding the *Additive Manufacturing* (AM) have been investigated and implemented. The analyze starts with a finger physical implementation, using 3-D printing technology. *Digital Light Processing* (DLP) is the 3-D printing selected process for finger structure manufacture. *Fused Deposition Modeling* (FDM) is another additive process used for outer protective layer and for its mold manufacture. A pressure-sensitive layer of Velostat is inserted between the outer protective layer and the finger structure. The paper presents a simple and efficient prototype of a finger, using a cheap and sufficient accurate solution based on new materials. The finger manufacturing process begins with the design of three-dimensional model for the mold without any supplementary equipment and classic technologies. Starting from a finger mechanical structure with its three phalanges, it is developed by adding a pressure sensitive layer of Velostat, towards a future desired artificial skin. Its electrical properties recommend it as a first layer that covers the printed finger structure. Another outer protective layer is also added. This finger structure will be integrated in a designed hand system.

Key-words: Mechatronic system, artificial finger, pressure-sensitive layer, 3D printing, Digital Light Processing, Fused Deposition Modeling.

1. Introduction

Accelerated new product development process towards market presentation becomes an important global challenge, involving new improved technologies. Among the new technologies, AM (*Additive Manufacturing*) enables users to build their desired objects directly from Computer Aided Design Phase, implying manufacturing cycle time reduction, up to nine times less than classic methods. The AM technologies are a new category of manufacturing starting from a virtual model, using special equipments. In an additive process, the desired object is created by laying down successive layers of material, as opposite of subtracting manufacturing which is cutting out the desired piece. The advantages of these new technologies are highlighted in complex parts with spatial shapes manufacture, impossible to be obtained with classical technologies. Furthermore, the part complexity does not influence the price.

The lately improvements of Additive Manufacturing technologies are connected with *Computer aided design* (CAD) and *Computer-aided Manufacturing* (CAM) software upgrades, especially for the new materials. New AM technology active development has been extended from industrial field to medicine. A main part of this practice is known as Rapid Tooling, integrating different tools and technologies, in order to increase the flexibility for small and medium production series. The flexibility idea is pointing out the short time of changing and adapting the tools with affordable costs.

The flexible tool concept has additional meanings, outer the boundary of their flexibility regarding the manufactured product, with important features:

- Tools or molds are required for small series production;
- Flexible tools normally connected to lower prices;
- Flexible tools concept implies the material type used for their manufacturing. The manufacturing molding process requires a series of development stages when the steel or the alloy having liquid state is casted in a cavity in order to copy it by passing through a solidity state. A main part of the process is the model manufacturing that has to have physically the same shape as the part, which will be molded and will give the external shape of the part. If the future part has some cavities, cores are used.

Models are divided in two categories: permanent models that are used many times and temporary models that are used for only one operation.

From their manufacturing point of view, the models can be manufactured as following:

- Handing manufacturing for the models made of wood;
- By cutting for steel models with regular shapes;
- By infusing or molding for the fusible models;
- Manufacturing by additive material.

The introducing and development of AM technologies provided a cheaper, more rapid method and sometimes a higher accuracy way for manufacturing all model and core types with a wide range of material sort. Starting from their virtual 3D model, with no other equipment or standard technologies, AM is a solution for rapid prototyping and small series products. The AM technologies are following some main stages as:

- The *Computer-aided design* (CAD) of the model that provides the entire description of the part, by using CAD software, a scanning system and so on;

- The CAD model is transferred through the sectional processor;
- The triangles of the model that was prepared before are ready for sectioning and computation;
- The part manufacturing;
- During the cleaning and finishing stages, it has to remove the auxiliary frames used for manufacturing or some other supplementary materials needed for the process in order to increase the dimensional accuracy and quality of the part [1].

2. Material and methods

Additive Manufacturing (AM) [2] fabrication processes using solid state raw materials have the ability to build physical models conforming to the three-dimensional virtual model. In these cases the material may be in threads and foils forms.

Processes based on material extrusion use a thread of different material qualities (polyamide, nylon, wax, etc.), which heats up to a few degrees below the melting point, then reduces its diameter to 0.12-0.15 mm by extruding it into a depositing device, a device that moves in the XOY plane to materialize a section of 3D virtual model.

This manufacturing process is based on heating the material to be deposited to its melting point and then depositing this melted material where necessary to build the desired pattern. The key of the process is to rigorously control the temperature at which the material is heated and maintained during the deposition. The used material may be a nylon, polyamide or plastic - ABS and PLA. The heating of the ABS wire is achieved at a temperature of 230 ° C, where the material is in a semi-liquid state, and can be further extruded through a very small diameter nozzle (0.254 mm or 0.127 mm).

The nozzle through which the semiliquid plastic material is extruded can be moved along with the heated head on which it is fixed. This displacement is done in the XOY plane, the movement being numerically controlled by the computer. Piece construction is mounted on a platform that moves vertically along the Z axis, movement is also controlled numerically by the machine.

In order to materialize *Fused Deposition Modeling* process (FDM), a FDM machine is required. A high performance graphics station or computer is also necessary. The STL (*Standard Triangle Language*) is the industry standard file type for 3D printing, using triangles to represent the surfaces of a solid model. All CAD dedicated software export their own formats into STL. The model is converted into machine language, sectioning it into successive layers, process the necessary geometric information and send the commands to FDM machine [3].

The plastic thread, running from a roll, enters in the heating head where it is heated up just below the melting point. Then, the thermoplastic material in the near-liquid state is extruded and deposited in thin layers. This means that only after the complete fulfillment of a layer is passed to the next layer, and deposition begins with the base layer of the piece. The melted material for deposition is precisely laminated to the outlet of the nozzle and is deposited immediately where the configuration of the piece from the respective layer requires it, the nozzle movement in the XY plane being controlled numerically. After deposition, the plastic fluid solidifies very quickly, each layer adhering perfectly to the one previously deposited. Figure 1 shows the schematic diagram of FDM technology.

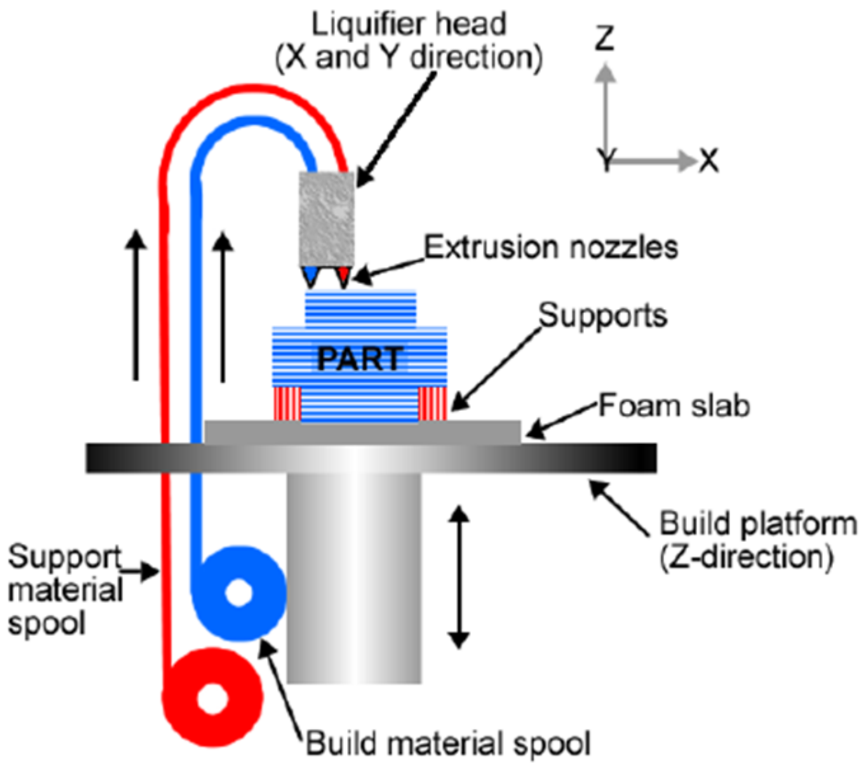

Fig. 1. The working principle of the FDM machine (color online).

The supports are not part of the piece, but they are required to support the piece's material during manufacture, where the piece has a complex configuration with internal voids. To increase the productivity of the fabrication, the supports are built with a lamellar structure. In this way, less material is used for supports and they can be more easily separated from the material of the work piece.

The advantages of FDM systems are: potential to approach zero waste manufacturing by maximizing material utilization, it uses economically accessible materials, easy to use FDM systems and no special conditions for installation and operation.

Disadvantages are due to the lower quality of the processed surfaces, mainly because of the scale effect, lower precision (0, 1 – 0, 2 mm) and relatively small sizes that can be manufactured [3].

3D printing technology is a well-planned and ready process for turning virtual models into physical objects. The steps of FDM technology are shown in the Figure 2.

Using FDM process, the molds are made of Acrylonitrile Butadiene Styrene (ABS). They can be used directly for injection of low fusible material too, if there are no other strictly imposed requirements regarding the material and surface qualities. The dimensional errors are inside the range of $\pm$ 0.2 mm as absolute values. If additional conditions regarding the surface quality are imposed, a supplementary finishing process will be required.

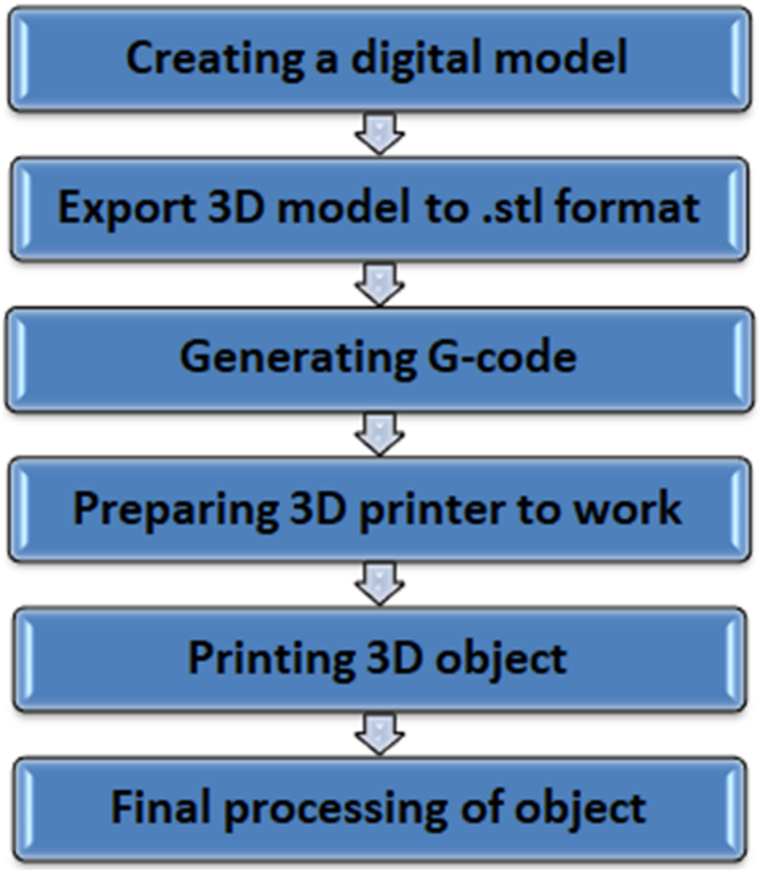

Fig. 2. Steps of the FDM process (color online).

Lately, FDM technologies and stereo lithography have gained popularity in 3D printing. They are used to produce high performance products. Because FDM technology is accessible, it is widely used in offices and educational institutions; however, its applications are limited compared to polymer-based polymerization technology where 3D printers are useful for creating better quality products surface. The development of photopolymers with desired properties, such as chemical composition, mechanical composition, bio-compatible materials and materials, will be useful in the creation of complex products and thus increase the application areas. Making resins according to the destination of models made with biocompatible properties when it comes to medical applications or materials with high elasticity when the pieces obtained are used for testing of springs and low melting resins when used in casting with models easily fused, respectively, or making materials for the development of transparent optical devices [1].

Due to cavity shape complexity, it was handmade, so some undesired dimensional or shape changes could appear. Thermoplastic extrusion technology begins like other rapid prototyping processes by designing the virtual image of the future object using a 3D editor or CAD program. So, the process starts with the creation of a three-dimensional model of the future piece. The designed mold is shown in the Figure 3.

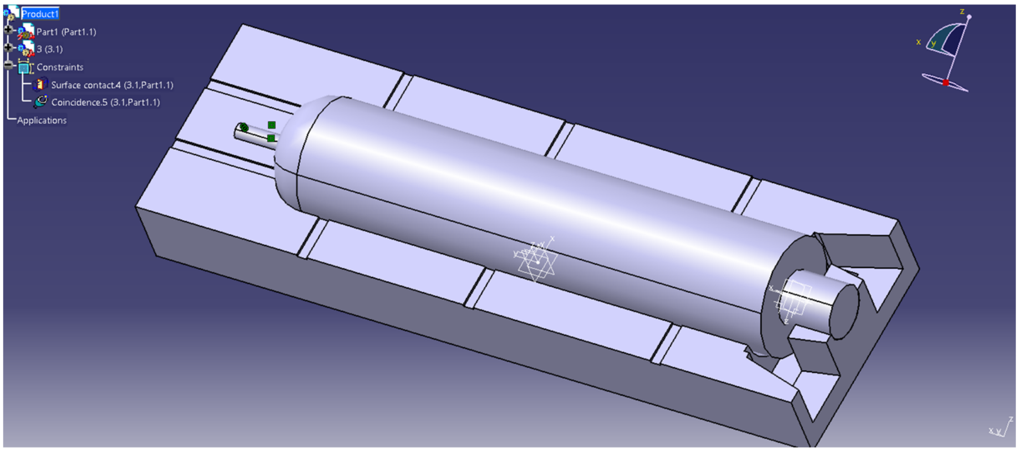

Fig. 3. Three-dimensional model of semi-mold and core (color online).

When 3D modeling is completed, the resulting file is transferred to .stl format, which is recognized by most modern 3D printers. The STL file with future restoration is processed by a special slicing program, which translates it into a control code G for the FDM printer. The slicing program with which the file was processed is Replicator G (Figure 4a) [4].

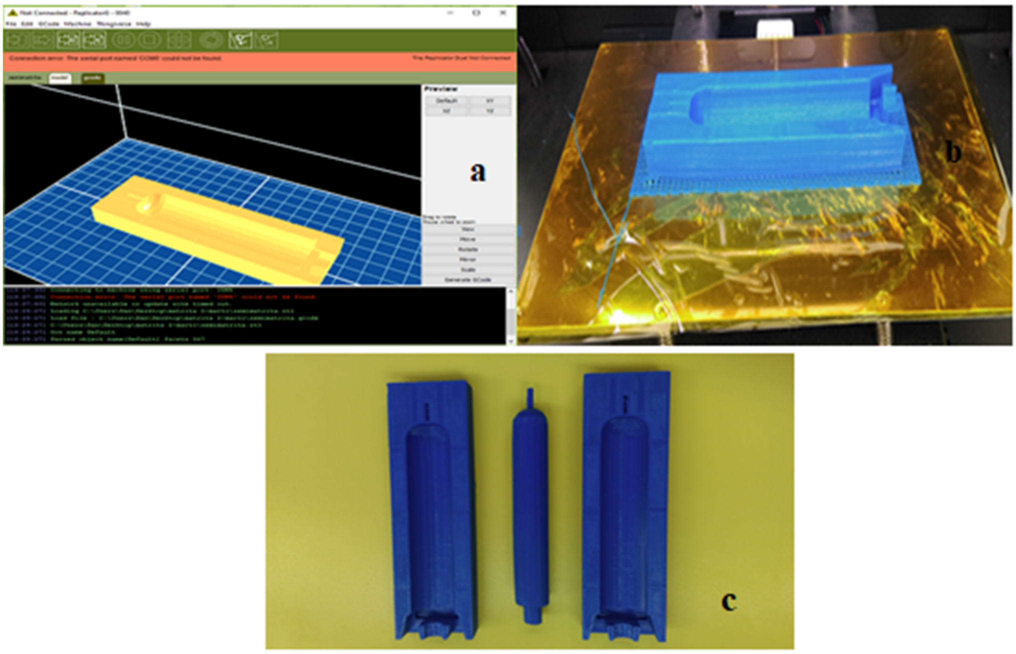

Fig. 4. a) Replicator G software interface; b) Fabricated semi-mold by fused deposition modeling on the work platform; c) Realized mold and core from PLA material (color online).

In the Mechatronic Faculty from "Politehnica" University of Bucharest, Romania, a FDM machine has been used to fabricate the mold for the outer layer of the finger. In the same university, a *Digital Light Processing* (DLP) additional printing technology has been chosen for finger structure implementation.

DLP is is an additive manufacturing process based on the use of UV light for the solidification of liquid polymer resins. DLP technology has as its principal element the DMD (*Digital Micromirror Device*) chip - a matrix of micro-mirrors used for fast spatial light modulation. Initially, the 3D CAD model is converted by the 3D printer's software into the cross-sections (slices) of the object, then the information is sent to the printer and the DMD chip. For each cross section of the 3D CAD model, the UV light emitted by a projector is modulated and projected by means of the chip on the surface of the polymer resin in the construction bucket. Each individual micromirror of the DMD chip projects pixels from the cross-section of the 3D model. Under the action of UV light, the photo reactive liquid (sensitive to ultraviolet light) solidifies in successive layers. Because the entire cross section is projected into a single exposure, the construction speed of a layer is constant regardless of the complexity of the geometry as shown in Figure 5.

3D objects of more complex geometries are printed with support materials that are later removed. The resin remaining in the construction tank can be reused for later printing. Certain printing materials may require subsequent curing processes in UV ovens.

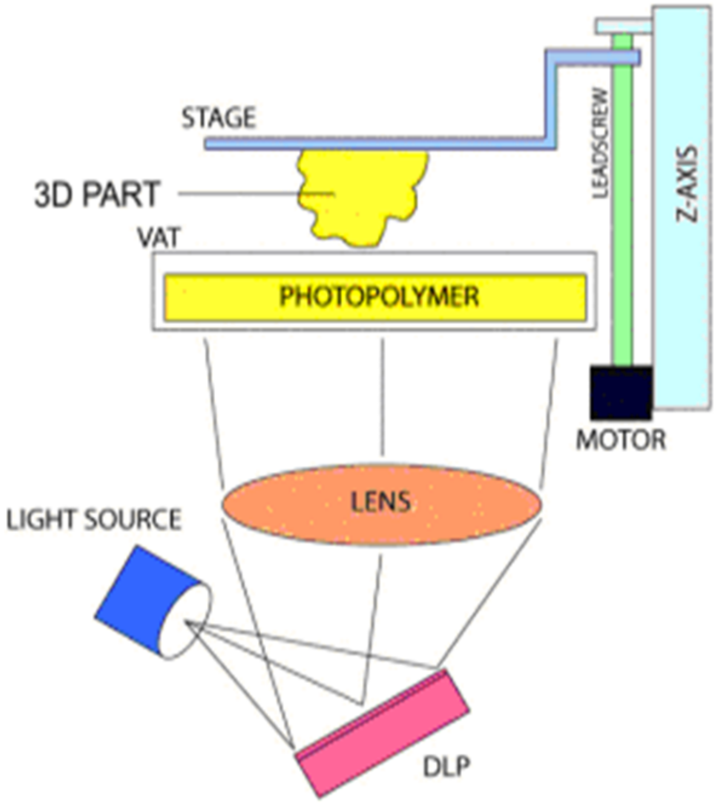

Fig. 5. DLP Digital Ligth Processing printing technology (color online).

Advantages of DLP (*Digital Light Processing*) are: fine and precise printed surfaces (use in the jewelry industry, dental technology and electronics), prototypes quite robust for processing, a variety of resins including bio-medical materials (certified for medical use) and transparent resins (prototypes in the packaging industry), stable printers with few moving parts. The technology allows the prototyping of complex and detailed geometry pieces, the high speed of printing for complex geometries and the simultaneous printing of multiple pieces (high productivity). Printed parts can be used as master molds for injection molding, thermoforming, metal casting.

Some disadvantages of DLP (*Digital Light Processing*) are: higher building materials, higher 3D printer prices (for large volumes), require post-processing operations (UV curing, removal of support material) require handling of resins [5].

The next step of this study is to realize the finger model by DLP technology. It starts in the same way like previous technology with achieving of object 3D model as shown in Figure 6.

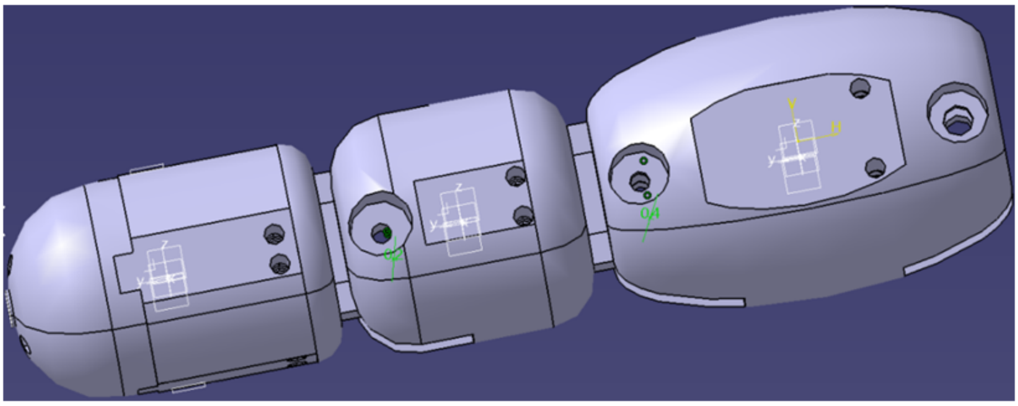

Fig. 6. Three-dimensional model of designed finger (color online).

The Creation Workshop software (Figure 7 – left) allows the view and positioning of the work piece on the work plane as well as mirroring, scaling, rotating.

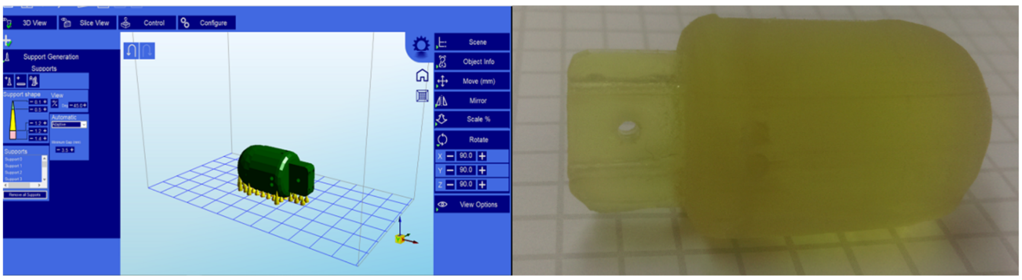

Fig. 7. Left – Creation Workshop software interface; b) realized phalanx by DLP technology (color online).

The Creation Workshop software also has the possibility to simulate the deposition of the layers during the construction process of the object as shown in Figure 8.

After all the steps have been completed, the proper printing begins. The program estimates the approximate time of realization.

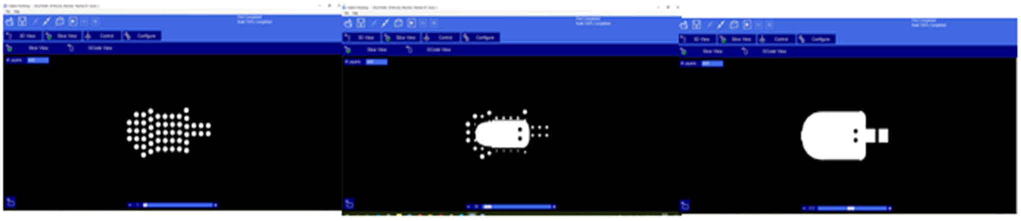

Fig. 8. Simulation of deposition layers (color online).

3. Experimental

After applicative researches, in Mechatronic Faculty from "Politehnica" University of Bucharest, Romania, a three phalanges finger has been obtained through DLP technology. Using FDM technology the casting mold for protecting coating which covers and ensures uniform pressure on the sensor was obtained as shown in Figure 9.

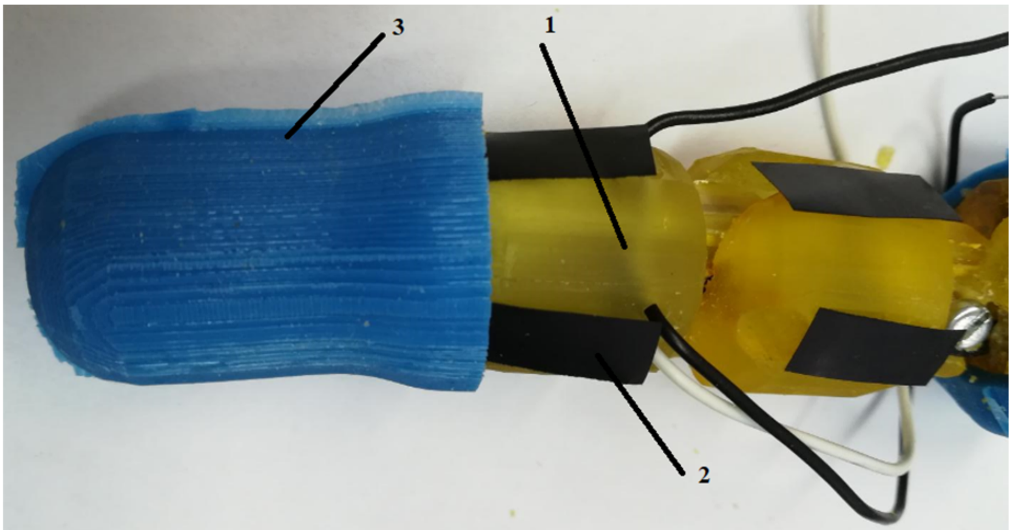

Fig. 9. Assembly of designed finger: 1. Phalanx realized by DLP technology; 2. Pressure transducer; 3. Protecting cover (color online).

Velostat or Linqstat is an opaque carbon–impregnated polyolefin, piezorezistive material used for wearable pressure sensors. Its resistance decreases when pressured, so it is used for flexible sensors. It is also recommendable due to its low cost. Its temperature limits are between 45°C to 65°C (–50°F to 150°F) and its Surface Resistivity is less than 31,000 ohms/sq.cm, making it a suitable choice [6]. The response characteristic of Velostat was analyzed in already developed experiments [7] as shown in Figures 10–13 [7] where its interaction with conductive or nonconductive objects was measured [7].

Fig. 10. The response characteristic of Velostat [7] (color online).

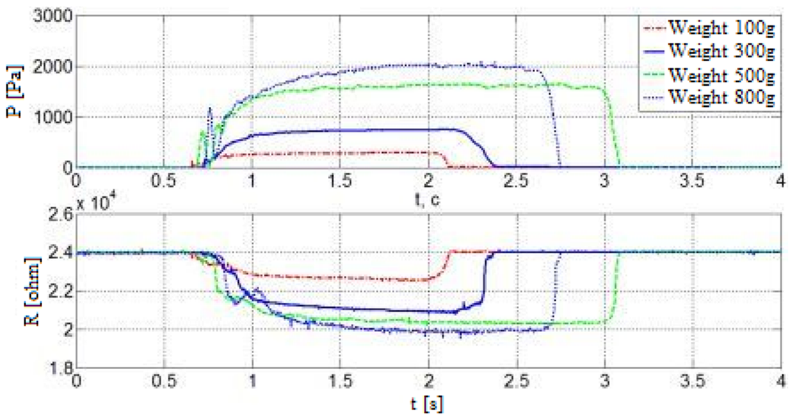

Fig. 11. Velostat interaction with conductive object [7] (color online).

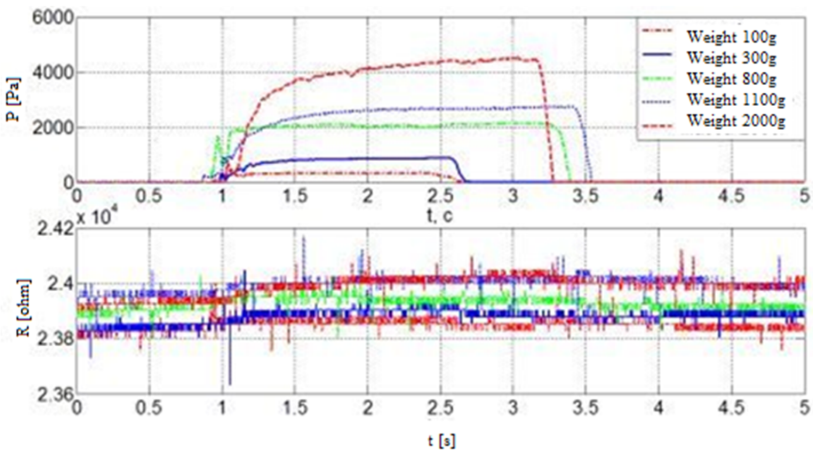

Fig. 12. Velostat interaction with nonconductive object t[7] (color online).

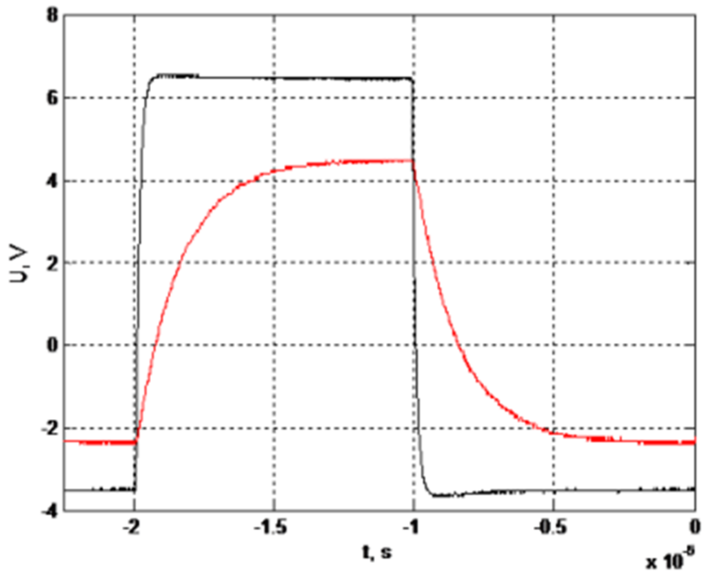

Fig. 13. Transient response of Velostat [7] (color online).

Based on experiments, the Velostat layer slightly reacts to the nonconductive objects. The tissue resistance varies negligibly, by 1.5 % when contacting with the nonconductive object but when contacting with the conductive object it varies by 30-50 The same electric experiments on Velostat were repeated in ”Politehnica” University of Bucharest, Romania, Faculty of Electronics, Telecommunications and Information Technology. Not all of them were perfectly reproducible. Our tests revealed that Velostat response has a strong dependence on stretching. It is very important if the material is pre-stretched in accurate resistance measuring.

Transient response experiments were also made. There is necessary about one second for the layer to obtain the same results as in Figure 13. Further investigations on Velostat, varying the surface and the number of successive layers are necessary. The use of the velostat allows an efficient implementation of the sensory feedback function for forearm prostheses [8] and intelligent robots [9].

4. Conclusions

Digital Light Processing (DLP) has been the 3D printing selected technology for finger structure manufacturing process. An articulated finger with three phalanges has been manufactured in Mechatronic Faculty from “Politehnica” University of Bucharest, Romania, using a 3D printer and a dedicated software.

In order to obtain an exterior protective layer for the manufactured finger, firstly a special designed mold was necessary. *Fused Deposition Modeling* (FDM) was the chosen technology for this mold. Then for the outer protective layer the same FDM process was used. This exterior layer has been realized in order to press and protect another pressure-sensitive layer especially added to enable the tactile sense.

The chosen and tested sensitive material was Velostat, a pressure-sensitive layer inserted between the outer protective layer and the finger itself.

Velostat electrical properties were analyzed from [7]. Own new tests on Velostat have been also developed and some important differences were noticed that will be further investigated in in "Politehnica" University of Bucharest, Romania, Faculty of Electronics, Telecommunications and Information Technology. The main noticed difference consists in transient response time that is very important and sensible longer than reported in Figure 13 [7]. After a pressing test, there is necessary about one second for the layer to obtain the same results.

An artificial hand is able to hold fragile objects through tactile feedback, so the proposed Velostat pressure sensitive layer has to be further investigated and evaluated for an intent future incorporation in the outer protective layer. 3D printed joints will be further investigated.

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