Additive manufacturing: design of a basic pivot articulation actuated with SMA wire

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***Abstract*—Today, the rapid advance of additive manufacturing, namely 3D printing, gives options and capabilities to simplify the fabrication of three-dimensional complex structures. In fact, such technology brings a real rupture comparing to conventional technologies in terms of design and manufacturing. Taking those advantages, this paper presents the design and the fabrication of a monolithic pivot articulation. First, the skeleton of the articulation is designed as a monolithic bloc. Then, the articulation is fabricated in one operation without assembly. To functionalize the articulation a Shape Alloy Memory (SMA) wire is utilized. Its advantage is the ease of integration thanks to the low diameter of the wire and the expected grooves within the printed structure, making possible the realization of miniaturized complex structures and the introduction of the actuation even inside this latter. The whole actuated structure has a centimeter size and serves as a proof of concept. Experiments are carried out to demonstrate the interest of the realized prototype and thus to highlight that 3D printing could be potential in the development of complex actuated structures.**

***Index Terms*—additive manufacturing, pivot articulation, shape alloy memory wire, micro-actuator.**

I. INTRODUCTION

Additive manufacturing, namely 3D printing, contribution is growing increasingly in several applications (robotics, miniaturization, mass customized product, etc) and receives increasing interest [1]. Such a technology brings a real rupture comparing to conventional technology in terms of manufacturing and design. As reported in [2]–[5] several complex structures have been made possible by additive manufacturing. These samples show clearly the power of 3D printing as a promising solution offering new perspectives to design innovative three-dimensional complex structures. The literature related to this technology is abundant [4], [6]–[9] and several technological developments exist since 1980.

The first 3D-Printing machine has been developed 30 years ago. Based on SLA principle (stereolithography), a laser beam polymerizes a liquid matter in order to built a three-dimensional object. Since, several technologies have been emerging utilizing different principles and various materials. The fabrication steps are generally common to almost all these technologies. According to the numerical chain, a 3D model is first designed using CAD (computer aided software) software. Then a STL digital model is generated from the CAD model. After that, the digital model is sliced into several thin layers along its cross-section. Based on the sliced model, the 3D printer starts to print the model from the bottom to the top, layer by layer. For exemple, the most advanced and adapted machine to print micro-systems is the ”Photonic Professional GT” from Nanoscribe company [10]. Photonic Professional GT is particularly interesting because it is the only technology offering highest resolution (sub-micrometer range), fast printing process combined with a large area writing (100x100mm^2) and easy to use. Reader can find an interesting and detailed review on 3D micro-additive manufacturing technologies in [11]. The review made a classification of 3D processes into three main groups including scalable micro-AM-systems, 3D direct writing and hybrid processes. Throughout the review, the principle and the recent progress of each process are described. Advantages and disadvantages of each processes are also presented.

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II. ARTICULATION DESIGN

Taking the advantages of such technology, our laboratory has initiated a project which aims to provide a framework allowing to design complex structure by combining basic articulations and flexures [12] in order to minimize assembly operations often costly in time and sources of hysteresis and of mechanical play. The main idea consists to design and demonstrate experimentally basic articulations (pivot, spherical...) in the first time. Then, latter, we combine these basic articulations in order to create more complex structures with more complex kinematics, dexterity and reliability. Within this aim, this paper deals with the development of a basic articulation. More precisely, the objective consists in the improvement of the pivot articulation presented in [12] in term of functionality and reliability. For that, an adapted structure and functionalization scheme is proposed. A shape memory alloy (SMA) wire is introduced as actuator such that we obtain an integrated actuated and functional pivot articulation. Concretely, the articulation is printed as a monolithic bloc with one operation without assembly where grooves and holes, made possible by 3D printing, are expected to guide the SMA actuator wire. Beyond the 3D complex shape, the articulation offers a wide range of angular displacements with microscopic resolution.

The organization of the paper is as follows. First, section-II addresses the design of a pivot articulation as a monolithic

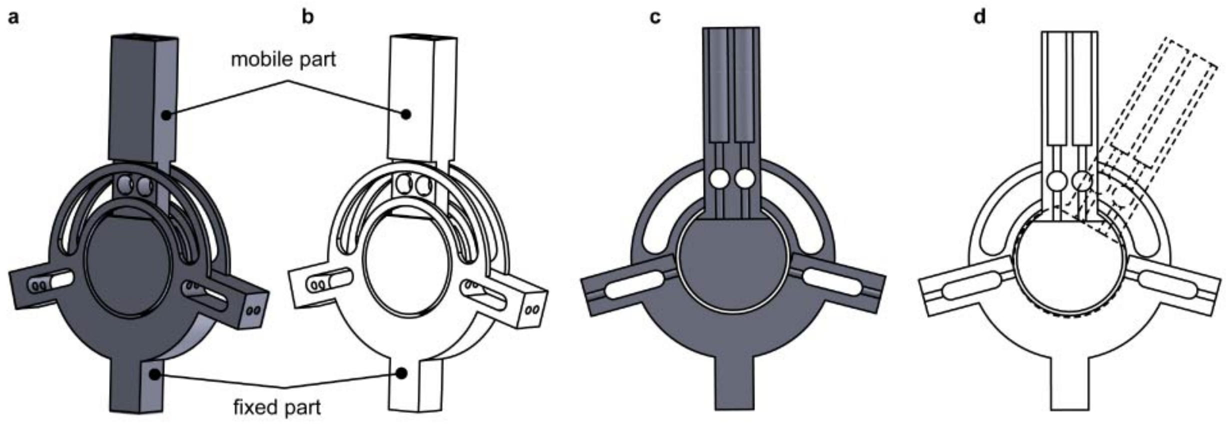

Fig. 1. Pivot articulation design. (a): CAD model of the articulation link. (b): wire representation of the CAD model. (c) and (d): cross section of the CAD model showing the expected grooves and holes allowing to introduce the SMA wire.

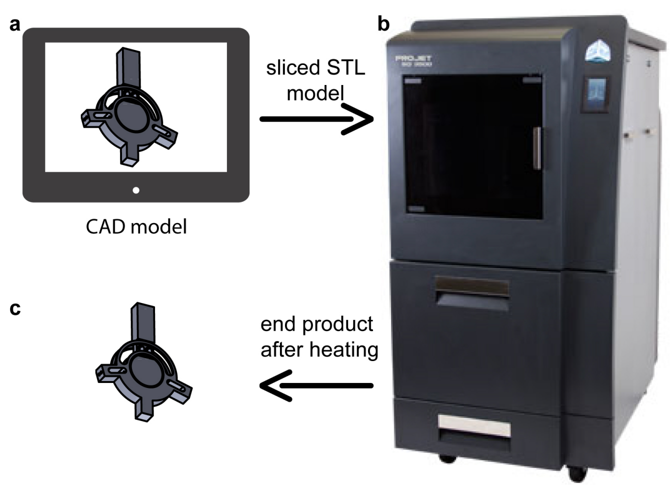

Fig. 2. 3D printing steps. (a): CAD design and data model generation. (b): 3D printing machine. (c): end product after heating.

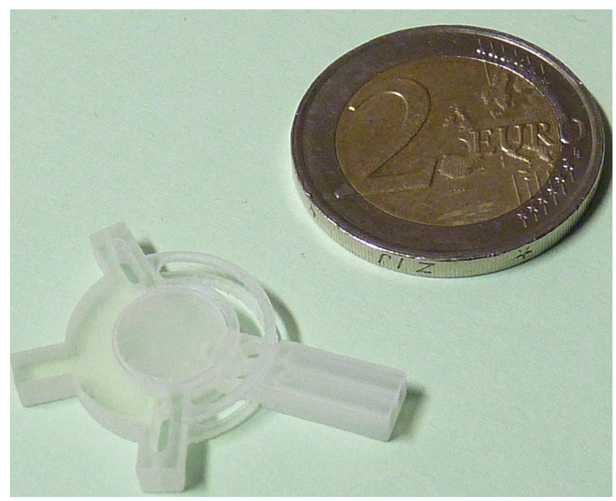

Fig. 3. Realized prototype.

bloc. Then, the fabrication of the articulation is presented in section-III. This section deals also with the functionalization of the articulation by introducing the SMA wire. After that, in section-IV, the experimental characterizations of the articulation are presented. Finally, section-V summarizes the works and presents some promising perspectives.

This section deals with the design of the pivot articulation taking into account the drawbacks of our previous design. Unlike the previous design, this new design is smaller and more compact. In addition, we add more holes and grooves in this new design in order to simplify the integration of the SMA wire. Figure 1 presents the designed pivot articulation. Likewise the previous design, it is composed of two parts: inner (fixed) part and outer (mobile) part. Figures 1a,b give a general view of the CAD model. Figure 1c shows a cross-section view where grooves and holes made to guide the SMA wire appear clearly. When the left (resp. right) SMA wire is supplied electrically and thus contracts, the mobile part turns on the left (resp. right), as depicted in Fig. 1d. This design is a result of several iterations where corrections and improvement were made from the initial design presented in [12].

III. REALIZATION OF THE ARTICULATION

This section deals with the fabrication and the functionalization of the articulation. First, the articulation is fabricated using a 3D printer. Then two SMA wires for actuation are introduced.

A. 3D printing of the articulation

As pointed previously, this articulation is a result of several improvement comparing to the articulation presented in [12]. Once the architecture design is fixed, friction and play are corrected by modifying the gap between the mobile and the fixed part of the articulation. Since there is no systematic

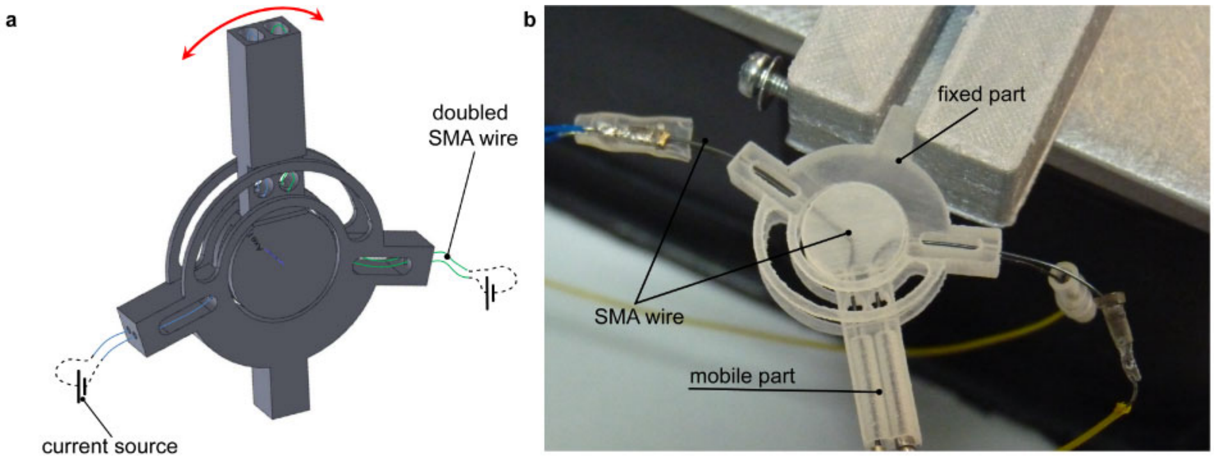

Fig. 4. Functionalization of the articulation by using SMA wire. (a): SMA wires distribution. (b): realized articulation equipped with SMA wires.

method to find an appropriate geometry and gap, we used a trial-error method. After several trials, we fixed the gap to 200 μm. Notice that design methodologies for smart materials based structures, for examples in [13], [14] are potential results that could be used to design this SMA based articulation. In these works, interval techniques and algorithms [15] are used to automatically find the optimal design of the structure that will minimize the dimensions and maximize the performances.

The designed model is sliced and the resulted data model is sent to the printer. To achieve this step, a PolyJet SD 3500 printer from 3DSYSTEM is used (see Fig. 2). A VISIJET M3 crystal material is used for the printing while paraffin is used as support material. Basically, with this machine, the three-dimensional CAD model is fabricated directly by adding material layer by layer. After printing, the piece is placed in a heated water in order to extract the support material (paraffin). The articulation resulted from this process is shown in Fig. 3.

B. Articulation functionalization

Likewise the previous design, functionalization is achieved by using SMA wire [16]. For that, two identical SMA wires of diameter of 0.3 mm are used. To simplify their integration, grooves and holes are expected within the structure (see Fig. 1c). Reader can refer to Figs. 4a,b to see respectively how the SMA wire is distributed within the articulation and how the SMA wire is introduced inside the realized articulation. Those figures show also how wires are powered and how they are positioned following a path defined by grooves and holes. Using the memory effect, each wire could be supplied independently to move the inner part of the articulation. Thus, when a wire is supplied, it tends to recover its initial shape which causes the displacement of the articulation and vice versa.

IV. Experimental tests

This section focuses on the experimental validation of the articulation. The idea consists to demonstrate the operation of the articulation when an electrical current is applied to each of the wires used for the actuation. More experiments, such as extensive static, dynamic, resolution and range characterizations, could be done but they are not the focus of this paper which is only focused on the functionalities verification.

A. Experimental setup

The experimental setup employed to verify the operation of the articulation includes the following components:
- the realized articulation actuated by SMA wire,
- a computer -with Matlab-Simulink software) and a National Instrument acquisition board that permits to manage the electrical voltage to be applied and the measurement,
- two current amplifiers which transforms the voltage from the acquisition board into sufficient current,
- and a Basler camera giving a visual feedback of the articulation.

B. experimental validation

Fig. 5 shows the experimental setup when the two SMA wires are supplied successively. This succession of electrical currents to the two SMA wires generates the rotation of the mobile part (joint displacement) in one direction first, and then in the opposite direction. Let us note the displacement caused by wire-1 as positive when electrically supplied. During this phase, the wire-2 is driven by the articulation and changes its shape as it is mechanically constrained. To generate a negative displacement, a current is applied to the second wire. In this case, the wire tends to recover its initial shape and vice versa. It is important to notice that the dynamic of the displacement is relatively low as shown in Fig. 5. The joint displacement sequence is highlighted in Fig. 6. In this sequence, Figs 6a-h are taken during the

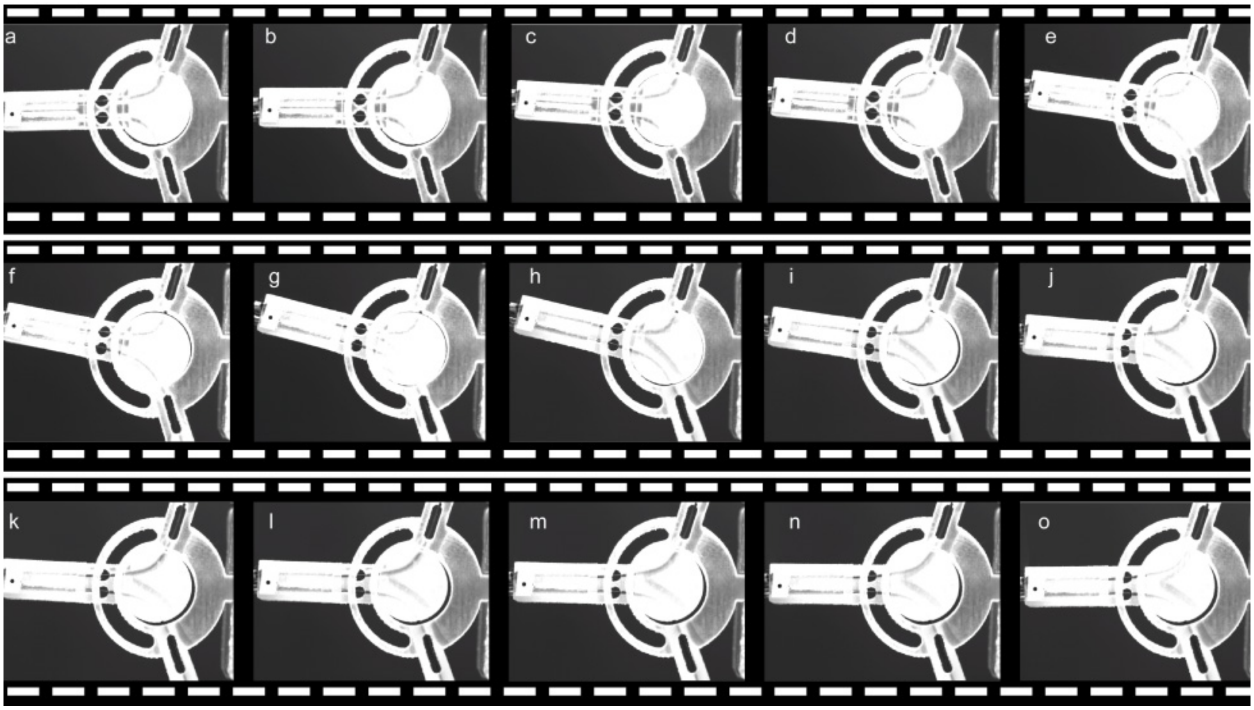

Fig. 6. Visual feedback sequence of the displacement of the articulation according to the actuated wire. (a to h): positive displacement caused by the actuation of the wire-1. (i to o): negative displacement caused by the actuation of the wire-2.

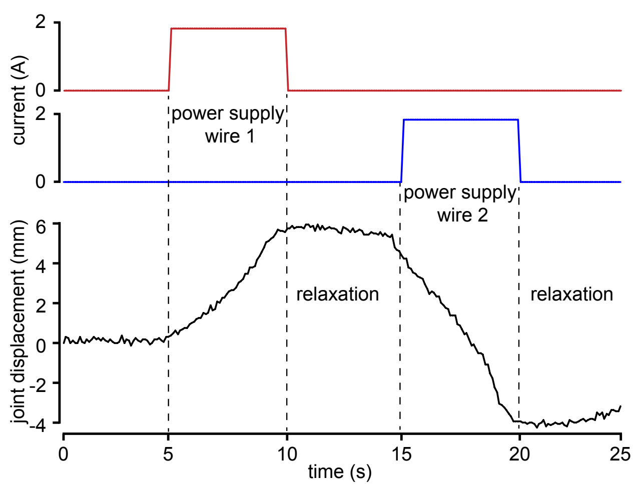

Fig. 5. Displacement of the extremity of the mobile part of the joint along Y axis according to time. The positive displacement is generated when wire-1 is actuated while the negative displacement comes with the actuation of wire-2. For each case, a square current impulsion with an amplitude of 2 A and a width of 5 s is used.

positive displacement when wire-1 is actuated. Figures 6h-o are taken during the negative displacement when wire-2 is actuated. The whole sequence clearly shows how the joint responds to an applied current to wire-1 and wire-2 respectively. Regarding to this experiment, the articulation is moving as expected and achieves a positive as well as a negative displacement. In addition, the angular displacement range of the articulation is important (around 30 deg) comparing to the resolution that could be achieved when SMA wires are used for actuation (see Fig. 6h). At this stage, this result demonstrates the principle of the presented pivot or joint articulation.

V. Conclusion

In summary, this paper presents the design of a pivot articulation actuated with SMA wire. This articulation is a result of the improvement brought to the design presented previously [12] in terms of design and functionalization. This work is a part of a general method which aims to fabricate complex structures without assembly. Made possible by 3D printing, this method aims to offer a new possibilities in terms of design and manufacturing by considering basic articulations as elementary bricks to construct complex structures.

Future works deal with advanced characterization of the realized articulation, its modeling and control. Future works also include the use of several basic articulations to realize more complex but dexterous actuated and integrated structure.

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