3D-Printing: a promising technology to design three-dimensional microsystems

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***Abstract*—System miniaturization remains an important challenge in the field of microrobotics. Several works have been raised in this context. Maybe the most known and widespread are MEMS devices based on clean room technologies. Although they give option to design small systems with mico/nano features, such technologies are limited to planar structures with two or three degrees of freedom (DOF). To tackle this limitation, a new approach is proposed in this paper. Instead of planar construction, we proposed here to design three-dimensional micro-systems by taking advantages of additive manufacturing technology, namely 3D printing. The final objective consists to design a monolithic structure in one operation without assembly. Then functionalization could be achieved by equipping the structure with actuators and sensors. Starting from the fact that any complex structure could be decomposed into basic elements such as articulations or flexures, this paper will focus on how articulations could be fabricated without assembly using 3D printing facilities. Combining those articulations which are considered as fundamental bricks will make possible to design complex monolithic structures. As an illustration, a pivot articulation is experimentally demonstrated using 3D printing.**

***Index Terms*—3D-Printing, additive manufacturing, micro-systems, articulation links, flexures, micro/nano-actuators, micro/nano-sensors.**

I. INTRODUCTION

To date, manipulating and characterizing small objects still a challenge for many emerging applications. From pick and place tasks to bio-medical applications [1] [2] [3] [4], such fundamental operations require special robotics systems with micro/nano features. To do so, researchers privileged system miniaturization. In this context, several studies have been raised since 1990. Perhaps the most known and widespread miniaturized systems are MEMS devices. Based on clean room technologies, they give many options to design efficient small systems with micro/nano features. This fact is attested by the abundant literature related to MEMS devices and miniaturized systems [5] [6] [7] [8] [9] [10]. However, several issues raise. The architectures are usually planar because of clean room manufacturing processes not allowing for example to design multi DOF MEMS architectures. The assembly of actuated mechanisms and measurement are often impractical for three-dimensional complex structures and micro-metric sizes. Otherwise, both measurement and actuation degrees of freedom are limited to XY translation. Moreover, their production is generally long and the rate of failure is high.

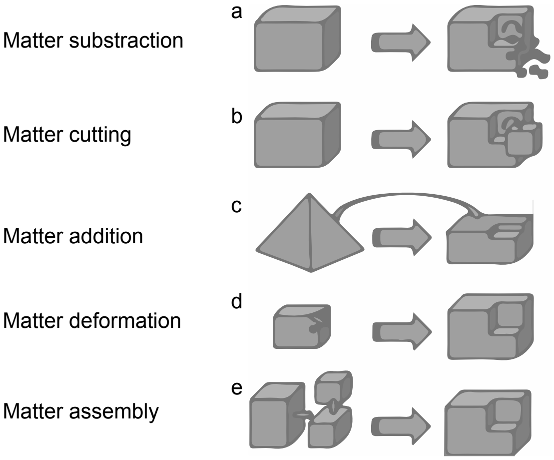

Fig. 1. Different methods of fabrication. a,b,d and e, conventional methods. c additive manufacturing.

To deal with those limitations, additive manufacturing seems to be a promising and efficient solution among existing technologies. In fact, latest advancing on additive manufacturing especially 3D printing offers new perspectives to design innovative micromechatronics systems and could pave the way for several applications. Such technology brings a real rupture comparing to conventional technologies (subtraction, cutting, deformation or assembly illustrated in Fig 1) in terms of manufacturing and design. For example, these processes enable to design 3D complex monolithic macro-structures as well as micro-structures. This could certainly save and minimize assembly operations often costly in time and sources of hysteresis and play.

Basically, with such technology three-dimensional model design (CAD model) can be fabricated directly as illustrated in Fig 2. The model construction is made by adding or combining material layer by layer. As illustrated in Fig 2.(b,c), each layer is a thin cross-section derived from the CAD model data. The thinner layer is, the best resolution is, allowing to reproduce small details. Taking these advantages, a new design approach is proposed in this work. So instead of planar construction, we proposed here to design three-dimensional micro-systems using 3D printing facilities. Of course, the final objective consists to design a monolithic structure in one operation without assembly. Then functionalization could be achieved by equipping the structure

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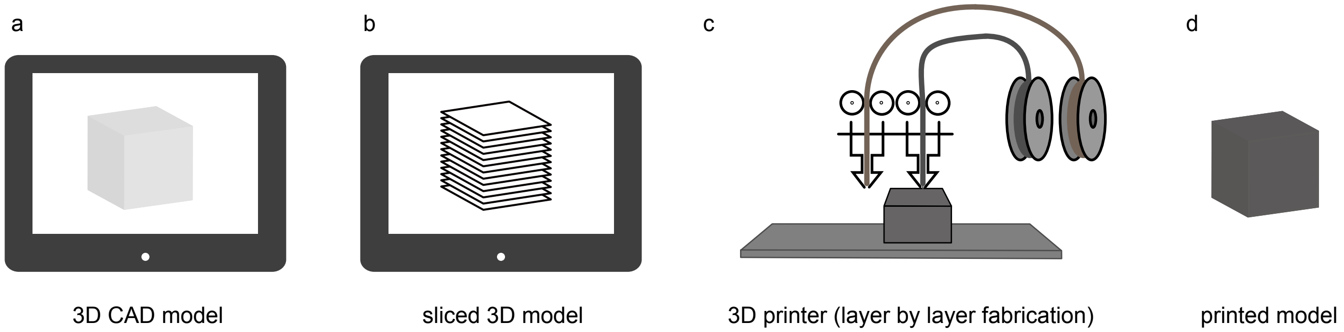

Fig. 2. 3D printing principle. a) 3D model design using CAD software, b) Before printing step, 3D model should be sliced using STL format, c) Based on STL data 3D printer fabricates the 3D model layer by layer, d) three-dimensional final product ready for use.

with actuators and sensors. However, this paper addresses only the aspect related to the design of basic articulations. Starting from the fact that any complex structure could be decomposed on a simple elements such as articulations or flexures supporting the main structure, this paper will focus on how articulation could be fabricated without assembly using 3D printing. Combining those articulations which are considered as fundamental bricks will make possible to design complex monolithic structures. As an illustration, a pivot articulation is experimentally demonstrated using 3D printing.

This short paper is organized as follows, section II deals with additive manufacturing features especially micro 3D printing. Section III addresses the proposed framework allowing to design complex structures by combining basic articulations and flexures. Section IV discusses the first results of the experiments carried out to design pivot articulation. Last section summarizes the work and presents some promising perspectives.

II. 3D PRINTING FEATURES

As shown previously in Fig 1, several fabrication technologies exist. Most of them are conventional and based on mechanical treatment such as milling, stamping, cutting, deformation or assembly. Basically, they consist to substract matter to fabricate given model. In opposition to those processes, matter addition known as additive manufacturing or 3D printing technology gives more options, capabilities and facilities to fabricate complex models. Recently, this technology is growing increasingly in several applications (bio-medical, robotics, etc) and received increased interest. This new technology brings a real rupture comparing to conventional technology in terms of manufacturing and design. For example, 3D printing enables to design three dimensional complex monolithic structures and gives option to integrate different functionalities (amplification, guidance, etc). Until now, almost all existing 3D printing technologies utilize passive materials, i.e. the printed structures are ”passive structures” without actuation and sensing capabilities. Meanwhile, actuators (piezoelectric, AMF, etc) and sensors could be reported independently on the final printed structure.

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 objects. Since, several technologies have emerged utilizing different principle and diversity of materials. However, the fabrication steps are common to almost all technologies. As shown in Fig 2, a 3D model is firstly design using CAD software. Then a STL digital model is generated from CAD model. After that, the digital model is sliced into a thin cross-section. Based on this, the 3D printer starts to built the model from the bottom, layer by layer until to finish the whole object. The literature related to such processes is abundant [11], [12], [13], [14], [15]. Perhaps the most advanced and adapted to print micro-systems is the ”Photonic Professional GT” from Nanoscribe company [16]. Photonic Professional GT is particularly interesting because it is the only technology offering highest resolution (submicrometer 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 [17]. 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.

III. FROM BASIC ARTICULATIONS TO COMPLEX STRUCTURES

As presented in the introduction, the proposed approach consists to design basic articulations that could be considered as bricks to build complex systems. In fact, robotic systems could be decomposed into several articulated links carrying an end effector. Each or a combination of articulations are driven by an appropriate actuators. All those elements are assembled in a certain manner to ensure a desired cinematic, dexterity and reliability in order to achieve given tasks. Although miniaturizing of such systems seems to be an intuitive approach to design microsystems, it has shown quickly its limits due to the manufacturing processes which

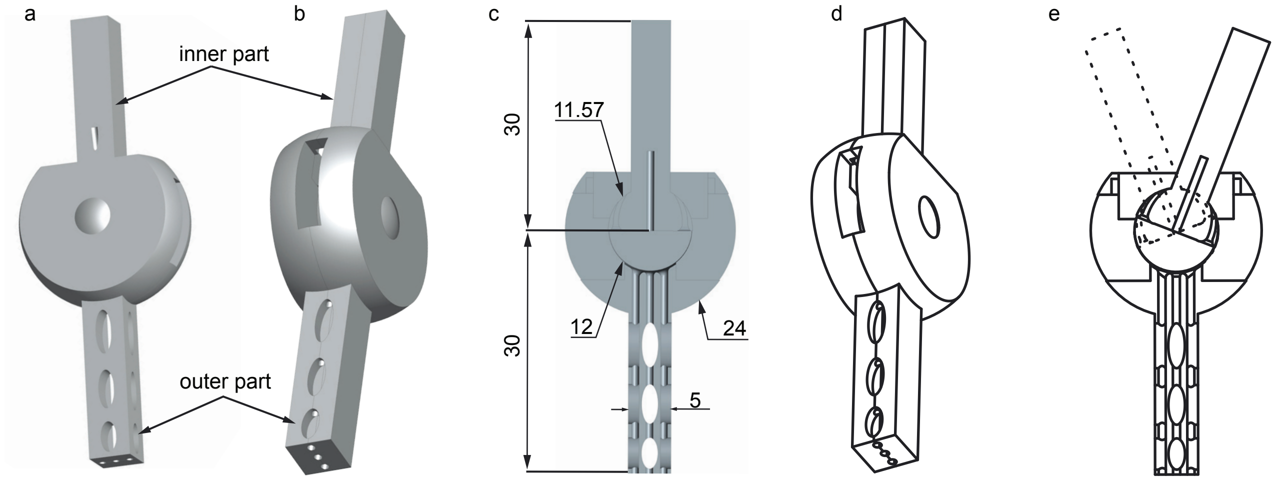

Fig. 3. Example of pivot articulation link. All dimensions are in millimeters (mm). (a) and (b), CAD model of the articulation link. (c) cross section of CAD model with main dimensions of the articulation. (d) and (e) wire representation of the CAD model and it's cross-section.

are planar. Moreover, articulation links are generally sources of friction and play comparing to flexures. However, the degree of maturity reached by 3D printing opens a promising perspectives to investigate this approach. With this technology, the whole system could be fabricated without assembly (end effector, structure and articulations). As shown in [18], an passive articulated model has been fabricated without assembly. Of course, system functionalization will be easier if 3D printers could combine active material such piezoelectric material with passive material. However, that is not the case until now. Doing with, functionalization could be achieved by equipping the articulations with external actuators as well as sensors.

Before designing a complex structure like parallel robot (delta, hexapod), we begin first by demonstrating the feasibility of each articulations (pivot, spherical or ball-joint, helical joint ...). This paper will particularly focus on the design and the feasibility of a pivot joint. This design will be the subject of the next section.

IV. DESIGN OF A BASIC PIVOT ARTICULATION

This section shows the design of a pivot articulation actuated using a shape alloy memory wire. This articulation is fabricated without assembly. Then the actuated wire is introduced inside a dedicated grooves and holes made possible using 3D printing. For practical raisons, we designed a centimeter version as a proof of concept.

A. Design

Figure 3 presents the designed pivot articulation using CAD software CREO. The articulation is mainly composed of two parts: inner and outer parts. A gap of 250μm is left to ensure a mobility of the inner part in respect to the outer part and to simplify the extraction of the support material. In this drawing board, Fig. 3(a,b,d) show a general view of the articulation. Figure 3(c) is a cross-section of the articulation where expected grooves and holes appear clearly. Made possible by 3D printing, they make easy to introduce the wire expected to actuate the articulation. This figure gives also the main dimensions of the actual articulation. Finally, Fig. 3(e) which is a wire representation, illustrates how the articulation moves. This design is a result of several iterations where corrections were made according to the result of the printed structures.

B. Realization

As pointed previously, this model is a result of several iterations where friction and play are corrected by modifying the geometry and the gap between the inner and the outer parts of the articulation. Since there is no systematic method to find an appropriate geometry and gap, we used a trial-error method. After several trials, we fixed the actual geometry and the gap to 250μm. Figure 4 shows the printed articulation using a PolyJet printer (3DSYSTEM). In respect to the printer features, a VisiJet PXL material is used to print the model while paraffin is used as a support material. After printing, the piece is placed in a heated water to extract the paraffin.

C. Shape alloy memory wire

For actuation, two identical shape alloy memory wires [19] of diameter of 0.3mm are used. To simplify their integration, grooves and holes are expected within the structure (see Fig. 3(c,e) and Fig. 5). In Fig. 5, a cross-section shows how those wires are connected to each others and to the ground. It shows also how they are positioned following a simple architecture. Using a memory effect instead of deformation, each wire could be supplied (power on) independently to move the inner part of the articulation (see Fig. 5(a,b)). When a wire is supplied, it tends to recover its initial shape which causes the displacement of the articulation and vice versa.

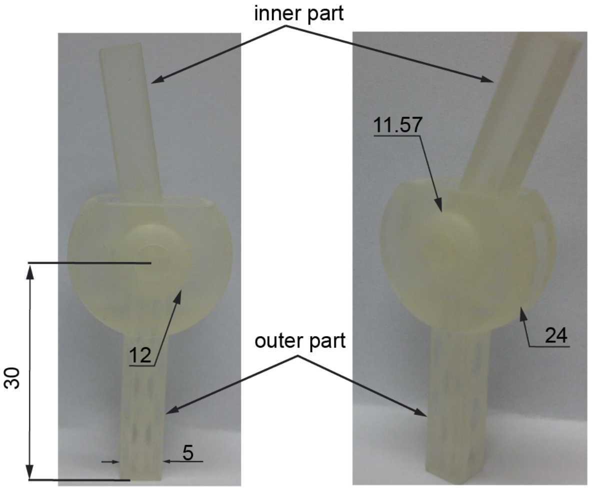

Fig. 4. Printed articulation using a PolyJet 3D printer from 3DSYSTEMS company.

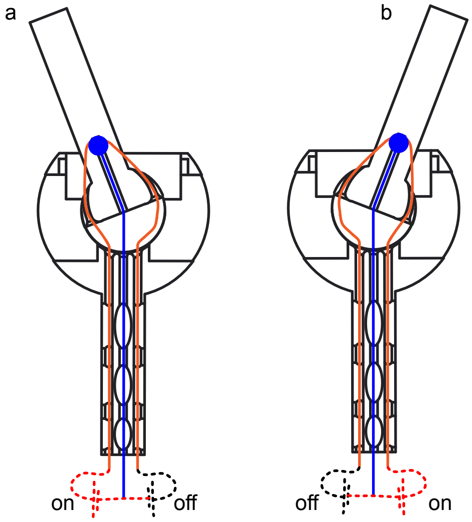

Fig. 5. Actuation principle of the articulation using shape alloy memory wire. red lines (shape alloy memory wire), dashed lines (power), blue line (ground).

V. CONCLUSION

In summary, this paper presents the genesis of a new method to design microsystems. Starting from basic articulations, the method aims to fabricate complex structure without assembly, i.e, monolithic structures. Made possible by 3D printing advanced technologies, a new possibilities are offered in terms of manufacturing and design. A proof of concept has been presented to demonstrate the interest of this method by designing a pivot articulation. Of course, several bricks should be designed to complete the method.

Future work would characterize and improve the actual design in terms of friction and play while retaining the same principle. Then, other links would be demonstrated. Another important improvement would be the feasibility of active materials in the printing process which is not the case untill now, to our knowledge. Achieving this improvement means that functionalization will be integrated within the 3D printing process, hence removing completely the assembly operations.

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