Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 11 (2017) 555 – 562

Procedia MANUFACTURING

27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017, 27-30 June 2017, Modena, Italy

Print-in-Place of Interconnected Deformable and Rigid Parts of Articulated Systems

F. Rosa[a*], M. Bordegoni[a], A. Dentelli[b], A. Sanzone[b], A. Sotgiu[b]

[a]*Dipartimento di Meccanica – Politecnico di Milano, Milano I-20156, Italy*
[b]*Graduated Student, Politecnico di Milano, Milano I-20156, Italy*

Abstract

One of the most fascinating possibilities of Additive Manufacturing technologies is their capability to realize objects that include various types of joints and moving parts. The research presented in this paper proposes to embed elastic elements in these joints in order to control their compliance. Two applications are also presented, in order to demonstrate, firstly, the practical feasibility of this innovative joint, and, secondly, the possibility to control joint elastic behavior in order to force the connected parts to automatically return to their initial positions when the actuating load is removed.

Peer-review under responsibility of the scientific committee of the 27th International Conference on Flexible Automation and Intelligent Manufacturing

Keywords: Print-in-Place; Multi-Material-Deposition; Additive Manufacturing; Flexi-Hand; Adaptive-Grip; Fused Deposition Modelling

1. Introduction

As far as the experience in the Additive Manufacturing (AM) field grows, it is becoming more and more evident that introducing AM in a production process is advantageous mainly in those situations where AM peculiarities can be fully exploited in order to realize “something” that cannot be realized otherwise, and/or to shorten and/or simplify a production cycle.

* Corresponding author. Tel.: +39-02-2399-8275; fax: +39-02-2399-8208.
E-mail address: francesco.rosa@polimi.it

Peer-review under responsibility of the scientific committee of the 27th International Conference on Flexible Automation and Intelligent Manufacturing
doi:10.1016/j.promfg.2017.07.149

More in detail, ISO/ASTM 52910:2017(E) [1] includes Design effectiveness, Part or product consolidation, Multi-part and compliant mechanisms among the "design considerations", i.e. "the issues that designers should consider when designing parts for AM". The first two issues express the "good design (for AM) practice" consisting in minimizing part number without losing any functionality, by exploiting the possibility to design parts for a desired property (minimum weight, desired compliance …). The last two issues introduce the possibility "to design working mechanisms, i.e., parts that move relative to one another, without the need for secondary assembly operations", as well as "other types of mechanisms cause relative movement between the input and the output through designed bending patterns".

In this perspective, this paper presents two case studies where two of these most "fascinating" and peculiar capabilities of the AM techniques are exploited to further improve two systems already manufactured with an AM (Fused Deposition Modelling - FDM) technique.

In particular, the Print in Place (PiP) and the Multi-Material Deposition (MMD) capabilities have been deployed to produce a stable junction between rigid (Poly-Lactic Acid, PLA) and flexible (Thermoplastic polyurethane, TPU) materials in order to manufacture elastic hinges without any assembly operation. Besides simplifying the assembly operations of the whole system, this solution allows also to create elastic hinges in positions no longer accessible during the product assembly phase.

The development of such a junction is not trivial, as the thermochemical reactions that can occur during the FDM process do not guarantee a sufficient and durable inter-layer adhesion between PLA and TPU. Their adhesion, in fact, is usually unwanted, since PLA is typically used to create the supporting structures of TPU components. A specific geometry has therefore been created to guarantee a proper and durable junction.

More in detail, this solution has been used to develop two end effectors: an adaptive robotic grip, based on the Fin-Ray Effect®, and a flexible hand, based on the well-known and wide spread "flexi-hands".

At a glance, each finger of the adaptive robotic grip is made of a triangular deformable structure, two edges of which are connected by means of rigid rods. Usually these rods are manufactured separately and then mounted on the triangular deformable structure. The developed junction allows for printing the rigid rods together with the deformable structure, simplifying the assembly operations of the whole robotic-grip system.

For what concerns the second case study, i.e. a flexible hand, two manufacturing solutions exist. The first and simpler method consists in manufacturing it as a single TPU flexible part. The second approach consists in printing several parts (phalanxes, palm and deformable junction elements), which have then to be assembled. The developed junction allows us to print all the parts in a single process (i.e. greatly simplifying the assembly process) and, at the same time, to have rigid phalanxes, useful, for example, to properly clamp objects.

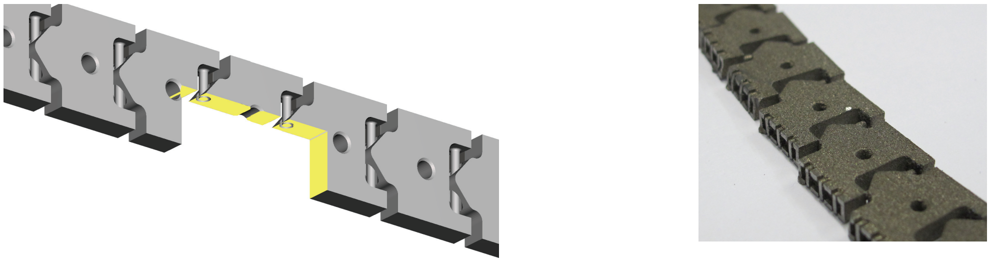
The paper is organized as follows. After a brief description of PiP and MMD techniques (Section 2), material properties are summarized and discussed in Section 3. Flexible junction conception and development are then described and discussed in Section 4, while Section 5 summarizes its application in the two selected case studies. Finally, Section 6 summarizes and discusses the findings demonstrated in the previous Sections.

2. Print-in-Place and Multi-Material Deposition

At a glance, the term *Print-in-Place* (PiP) is used in this paper to designate the technique consisting in printing objects made of different and separated but "intertwisted" parts, so that relative displacements among these parts will be possible when the printing process is completed. Figure 1 shows a sample application (i.e. some links of a simple bracelet) of this technique.

Designing PiP systems is one of the research topics in the field of "Design for AM". These systems, in fact, can incorporate several types of joints capable to inter-connect many moving parts. Moreover, the intrinsic additive nature of the process allows for generating these joints even in positions no longer accessible when the process is completed, generating mechanisms not realizable with the "conventional" manufacturing processes, which require part assembly. This possibility has made viable designs that were unimaginable without AM. The realization of such systems is nevertheless not simple and immediate: sufficient high accuracy and precision are essential to print them, since a precise control of the clearance among the parts is crucial for the proper functioning of this kind of systems.

While PiP allows for the creation of free joints, an elastic behavior is often needed in articulated systems, in order to control joint flexibility and/or to make the interconnected parts to return to their initial positions when the applied load is removed. Such a result is typically obtained by connecting the “rigid” parts with a material capable to grant to the joint the desired properties. For example, Cutkosky and Kim [4] developed Shape Deposition Manufacturing (SDM), which is a hybrid technique in between machining and molding that allows for building up “multi-material structures, with intentional compliance and damping”, in order to “enable small, bioinspired robots to emulate some of the characteristics that are found in animals, which contribute to the animals’ performance in locomotion over uncertain terrain”. From a functional point of view, similar results can be obtained by means of the so called *Multi-Material-Deposition* (MMD) technique. In a nutshell, MMD consists in the possibility to depose different materials even within each single layer. As a result, it is possible to print objects made of different materials with very different properties, without the need of any assembly operation. In the FDM printers, this technique is usually implemented by adding one or more additional extruders, and using each of them to depose a different material.



(a) (b)

Figure 1: Sample Print-in-Place Application: (a) CAD model (sectioned along the yellow surfaces); (b) articulated system (before sand blasting) printed in ASTM 316L with a Renishaw AM 250 SLM machine [1]

The combination of the PiP and of the MMD techniques enables a further degree of freedom in the design process of elastic joints. Designers are no longer obliged to design the elastic connection element as a separate part and to be concerned about how to assemble the joint. The elastic element can be manufactured directly in place, and the resulting joint will be “automatically” mounted during the manufacturing process, overcoming the need of designing complex assembly procedures.

In order to demonstrate the practical implications of this idea, the realization of an elastic joint is presented and discussed in the next Sections. In particular, this joint is realized with a double-extruder FDM printer (Sharebot NG), using *PolyLactic Acid* (PLA) to realize the rigid parts, and *ThermoPlastic PolyUrethane* (TPU) to print the elastic connecting elements. The next section summarizes the properties of these two materials.

3. PLA and TPU properties

PolyLactic Acid (PLA) is a biodegradable and bioactive thermoplastic aliphatic polyester. PLA can be processed, like most thermoplastics, into fibers (for example, using conventional melt spinning processes) and films. As a consequence, and thanks to its high temperature stability and the possibility to form a highly regular stereo-complex with increased crystallinity by physically blending the polymer with Poly-D-Lactide (PDLA), PLA is widely used as a feedstock material in desktop fused filament fabrication-based 3D printers.

TPU is a block copolymer consisting of alternating sequences of hard and soft domains formed by the reaction of di-isocyanates with short-chain diols (so-called chain extenders) and di-isocyanates with long-chain diols. Fine-tuning of TPU structure to the desired final properties is achieved by selecting the proper ratio and structure of the compounds. The final resin consists of linear polymeric chains of low polarity segments (which are rather long and called soft segments), alternating with shorter, high polarity segments (called hard segments). The polarity of the latter segments creates a strong attraction between them, which makes them highly aggregated and ordered, resulting in crystalline or pseudo-crystalline areas embedded in a soft and flexible matrix. These areas act as physical cross-links, which account for the high elasticity level of TPU, while its elongation characteristics are due to the flexible chains. A deep discussion of these properties of the TPU can be found in [5]. Since cross-links disappear under the effect of heat, extrusion and injection molding processes are applicable to these materials. TPU is, hence, also adapt to print highly flexible parts using the FDM technology.

Materials realized by blending TPU and PLA are currently under study and development. For example, Ahmed et al. [6] studied the effects of blend composition and foaming conditions on micro-structure and properties of PLA/TPU blend foams, while Feng and Ye [7] studied how to improve PLA toughness by blending it with a TPU kind of material with high strength and toughness. Nevertheless, it is also well known that their inter-layer adhesion is very limited. Practically, if a TPU layer is printed directly on a PLA layer (or vice versa), they will separate after so few load cycles, that PLA can be used to support TPU objects, as shown by Norée [3]. Therefore, a peculiar geometry of the parts has to be conceived in order to guarantee an adequate duration of the elastic hinge introduced in the previous section.

4. Joint structure development

Since two materials (a “soft” and a “rigid” one) are required to realize a flexible junction between two rigid parts, a double extruder FDM printer has been used. In particular, a dual extruder *Sharebot NG* printer has been used to manufacture the samples described in this Section and the prototypes described in the next one. On the basis of the properties described in the previous Section, the Thermoplastic Poly-Urethane (TPU) has been selected as soft material because of its good flexibility and its capability of returning to its original shape after load removal, while the Poly-Lactic Acid (PLA) has been selected as rigid material.

As anticipated, the main obstacle to the practical realization of a flexible junction using these two materials is the quite well known TPU-PLA inter-layer limited adhesion.

Figure 2 shows a simple sample that has been realized mainly to verify and show its practical inadequacy. It has been realized by simply printing three stacked strata. The second central continuous stratum (white) is in TPU, while the first and the third (purple) strata are in PLA and have a gap in the middle to allow for the bending of the central TPU stratum, and hence to permit the sought relative movement between the right and left rigid “sides” of the object. As expected, after very few bending cycles the strata separate (Figure 2).

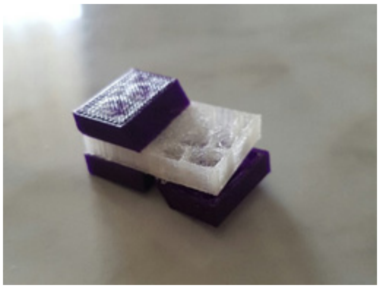
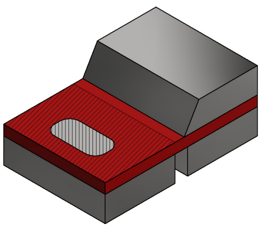


Figure 2: Simple sample realized by deposing a TPU stratum (white) between two PLA strata (purple). After few cycles the PLA parts (purple) got completely detached from the TPU part (white).

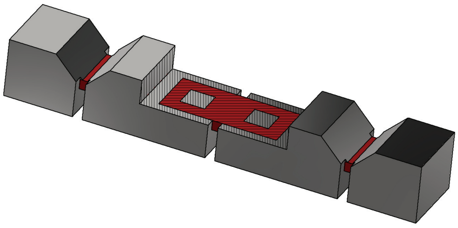


(a) TPU parts are red colored, PLA parts are gray colored

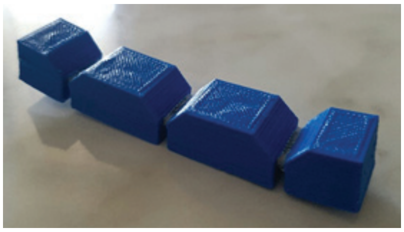
(b)

Figure 3: first attempt: junction CAD model (a) and test samples (b). The CAD model has been sectioned (where hatched) in order to show the pillar that connects the two PLA strata.

To overcome the TPU and PLA inter-layer limited adhesion issue, some small pillars of PLA passing through the TPU stratum have been added in order to guarantee a permanent and stable connection between the two rigid PLA strata. As a result, since the TPU stratum completely embrace these pillars, the relative displacements between the two materials are also completely prevented. Since the inter-stratum adhesion of this solution (Figure 3) is relatively independent from the contact area between PLA and TPU, it is applicable also with a quite low infill, easing the research of a compromise between junction flexibility, PLA parts stiffness and low weight. After some tests, the infill has been set at about 20% for PLA and at about 15% for the *2 mm* thick stratum of TPU. The shape of the rigid portions is designed to avoid interferences when the junction is bent up to the desired angle.
The practical application of the solution depicted in Figure 3 immediately revealed its limit: the upper PLA stratum has the tendency to warp because of its own thermal shrinkage, since its bonding with the underlying TPU stratum is not strong enough. To overcome this problem, the TPU stratum has therefore been "confined" between two lateral PLA walls and the number of PLA pillars has been increased. Figure 4 shows the final design of the junction.



(a) TPU parts are red colored, PLA parts are gray colored



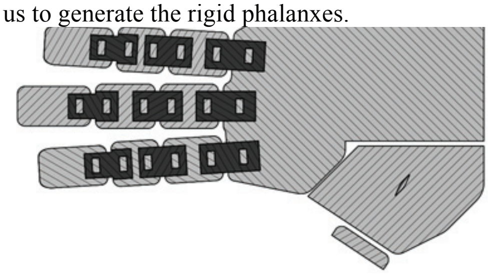
(b)

Figure 4: final design of the junction: CAD model (a) and 3D printed object (b).

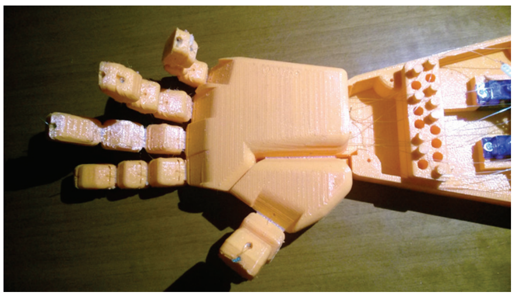
5. Case studies

5.1. Flexi-Hand

The flexi-hand is quite well known among the so-called *makers* and many models are even available to download for free. At a glance, all the existing solutions of 3D-printed flexible hands can be clustered in two main groups. The first solution consists in realizing the hand in several parts that have to be then assembled. Printing the whole hand with flexible material is the other solution. The first solution allows for obtaining the needed flexibility for the movements and the stiff phalanxes to clamp objects, but it requires several assembly operations. The second solution, on the other hand, allows us to print the hand in a single process (simplifying its realization), but it does not allow us to generate the rigid phalanxes.



(a)



(b)

Figure 5: final design of the Flexi-Hand: CAD model (a) and prototype (b).

The adoption of the junction described in the previous section allows us to combine the advantages of both these approaches: it is printed in a single process, and allows us to realize stiff phalanxes.

Figure 5 shows the final design of the hand and the realized prototype, where the junction previously described has been used to realize the flexible junctions between the phalanxes of each finger.

Concerning the actuation of this Flexi-Hand, each finger is actuated independently by means of a wire passing through a channel that connects the fingertip to the wrist. One end of each wire is therefore blocked at the corresponding fingertip by means of a node, while the other end is connected to a pulley actuated by a servomotor.

As a result, the closure of each finger is obtained by pulling the wire by actuating the corresponding servomotor, while its opening is left to the intrinsic elasticity of the junctions. Nevertheless, if necessary, hand opening can be also realized by means of wires and servomotors, in order to, for example, apply relevant forces also in this phase, and/or counteract external forces that cannot be counterbalanced only by means of the elastic reaction forces generated by the junctions. An Arduino board based control system is used to coordinate the movements in order to replicate the desired gestures.

5.2. Adaptive-Grip

Even if grasping is one of the most common and important tasks of a robotic system, some margin to improve it are still available. In particular, the developed solution has been conceived to quickly and efficiently improve grasping system usage flexibility by making it adapting to grasp product of variable dimensions and, at the same time, capable to automatically and effectively control the grasping forces to avoid damaging soft objects.

One of the most famous adaptive-grip is the so-called *Festo Fin-Gripper®* [8], whose fingers are the result of a Biologically Inspired Design process. Their kinematic, in fact, has been "inspired" by the unfolding movements of the fins of several kinds of fishes. At a glance, the longitudinal concurrent fibers of the V-shaped fingers (white parts in Figure 6) are flexible and hinged to several rigid rods (orange parts in Figure 6). This particular design allows the finger to bend in the direction of the applied grasping forces, and, hence, to adapt finger shape to the object being grasped.

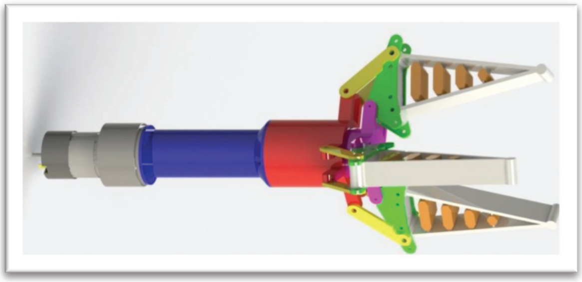
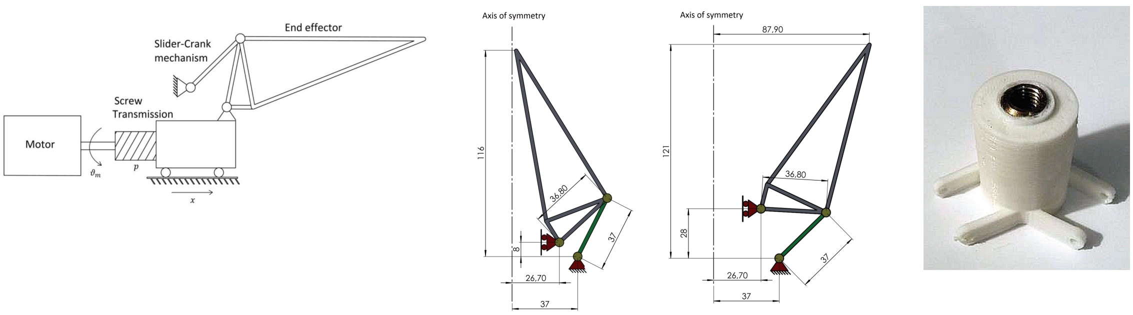


Figure 6: adaptive grip.



(a) (b) (c)

Figure 7: adaptive grip kinematic.

Several approaches can be followed to design the end effector of this kind of adaptive grip.

For example, Birglen [9] presents a method based on the analysis of the kinematic pre-shaping of these self-adaptive “fingers”. The main goals of this method are the optimization of the geometrical parameters of the “passive elements” and the selection of the proper joints, with the aim to “obtain particular kinematic relationships between the motions of the phalanges”.

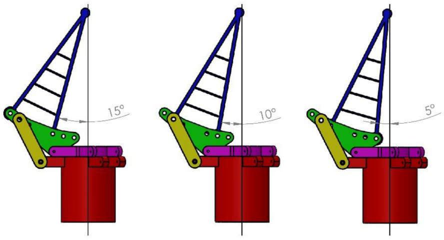


Figure 8: system possible configurations.

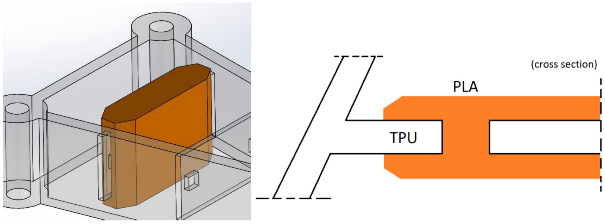


Figure 9: realization of the flexible connection between the rigid rods (orange) and the flexible portion of the finger (transparent).

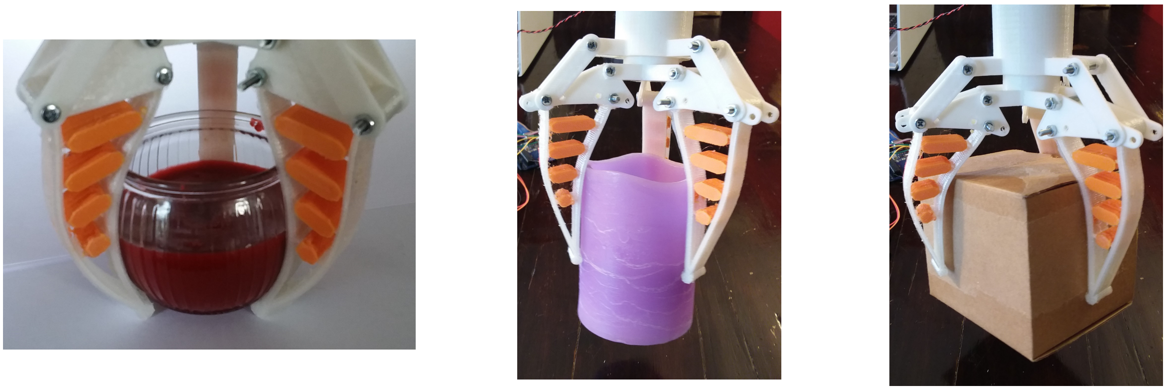


Figure 10: adaptive grip prototype.

Figure 7a shows the kinematical schema of the system discussed in the present paper. The end-effector (composed by three fingers, shown in Figure 7b in opened and closed positions) is actuated by a servo-motor. Finger and mechanism dimensions (Figure 7b) have been determined in order to minimize the axial displacement of the top point of the finger itself, i.e. to obtain an almost rectilinear trajectory of finger top point, within the predefined operating range. The screw transforms motor rotary motion to the rectilinear motion required to move the slider-crank mechanism to impose to the fingers the appropriate motion. Figure 7c shows a threaded insert embedded in the part (purple-colored in Figure 6) that actuates the mechanism by sliding inside a hollow cylinder (red part in Figure 6).

In the prototype discussed in the present paper, three couples of holes have been realized to connect the finger to the mechanism in different positions in order to widen the range of dimensions of the object that the system can grasp (Figure 8).

Usually the rigid rods are mounted during the assembly phase. In order to speed and simplify the manufacturing cycle, the fingers of this system have been conceived and developed by applying the solution discussed in Section 4. In particular, this solution has been adopted to realize the hinges that connect the rigid rods to the arms of the V-Shaped fingers.

Figure 9 shows how the flexible connection between the rigid rods (orange) and the flexible portion of the finger (transparent) has been realized. Practically, the two arms of the V-shaped finger are connected also by several flexible "plates". In order to make them stiff enough, a rigid structure is realized by printing two PLA strata around these TPU flexible "plates". As explained in Section 4, these two PLA strata are connected by several small pillars, in order to compensate for the scarce TPU-PLA inter-layer adhesion. In order to preserve finger arms flexibility, an adequate clearance has been allowed between the PLA strata and the TPU "plates".

Figure 10 shows the manufactured prototype of the adaptive gripper in action. Its capability to grasp objects of different size and shape is quite evident.

It is finally worth underlying that, even if the prototype has been realized with three fingers, the developed solution can be adopted to realize grips with more fingers. Also in this case an Arduino board based control system is used to actuate the servomotor.

6. Conclusions

This paper discusses in detail an innovative method to realize an elastic joint between two rigid portions by fully exploiting the capabilities of the Additive Manufacturing technologies, according to the design guidelines of ISO/ASTM 52910:2017. In particular, the realization of this joint is based on two of the most fascinating capabilities of these manufacturing technologies: Print-in-Place (PiP) and the Multi-Material Deposition (MMD).

The two practical applications discussed in the paper, besides the practical feasibility of the developed solution, demonstrate that there is still margin to improve and exploit AM by further improving two products commonly manufactured with these technologies.

However, the proposed solution may open up new possibilities, allowing us to realize solutions that, otherwise, cannot be manufactured. For example, this solution can be used to realize hinges in positions no longer reachable during the assembly phase.

References

[1] ISO/ASTM 52910:2017(E), Standard Guidelines for Design for Additive Manufacturing, March 2017. DOI: 10.1520/ISO_ASTM59210-17
[2] AddMeLab, www.addmelab.polimi.it, last accessed 27 February 2017
[3] Norée, D., Does TPU stick to TPU to PLA when 3Dprinted, https://www.youtube.com/watch?v=AlpNyxZWqbw, last accessed 27 February, 2017
[4] Cutkosky, R., M., Kim, S., Design and fabrication of multi-material structures for bioinspired robots, Phil. Trans. R. Soc. A, 367 (2009) 1799–1813, doi:10.1098/rsta.2009.0013
[5] Qi, H.J., Boycel, M.C., Stress-Strain Behavior of Thermoplastic Polyurethane, Mechanics of Materials, 2005, 37(8):817-839
[6] Ahmed, M. F., Li, Y., Zeng, C., Effects of blend morphology and operating parameters on foaming of polylactic acid/thermoplastic polyurethane, SPE ANTEC™ Indianapolis 2016, pp. 1801-1805
[7] Feng, F., Ye, L., Morphologies and Mechanical Properties of Polylactide/Thermoplastic Polyurethane Elastomer Blends, Journal of Applied Polymer Science, 2011, 119:2778–2783
[8] Festo, MultiChoiceGripper, 2009, https://www.festo.com/net/SupportPortal/Files/333986/Festo_MultiChoiceGripper_en.pdf, last accessed 17 January 2017
[9] Birglen, L., The kinematic preshaping of triggered self-adaptive linkage-driven robotic fingers, Proceedings of the 1st International Workshop on Underactuated Grasping, UG2010, August 19, 2010, Montreal, Quebec, Canada (http://www.polymtl.ca/labrobot/pdf/UG2010_3.pdf)