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Review

Additive manufacturing of non-assembly mechanisms

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ABSTRACT

Fabrication of complex and multi-articulated mechanisms is often seen as a time consuming and demanding process. The development of functional multi-articulated mechanisms that could be fabricated in a single step without the need for post-manufacturing assembly is therefore very attractive. Additive manufacturing (AM) has been pointed out as a feasible solution due to its numerous advantages and high versatility in comparison to other manufacturing techniques. Nevertheless, AM techniques also present different shortcomings that limit the complexity of the mechanism for single step fabrication. Here, we review the applications of AM techniques in fabrication of non-assembly multi-articulated mechanisms and highlight the involved challenges, thereby providing a perspective regarding the advantages and limitations of current AM techniques for production of complex mechanical devices. The paper starts off with basic joint elements in rigid-body and compliant configurations and proceeds with presenting an overview of multiple arrangements of joints and assemblies with embedded mechanical components. For every case of non-assembly fabrication, the limitations of the applicable AM processes are presented and further discussed. This work concludes with a discussion of the major shortcomings found in current non-assembly mechanisms fabricated by AM and recommending alternative techniques and future developments on AM.

1. Introduction

Fabrication of complex and multi-articulated mechanisms is often seen as a time consuming and demanding process. Conventional manufacturing techniques are often limited to simple mechanisms, thus requiring complex assembly procedures to construct multi-articulated mechanisms. For that reason, the development of functional multi-articulated mechanisms that could be fabricated in a single step without the need for post-manufacturing assembly is very attractive. Mechanisms fabricated whose fabrication process does not involve an assembly step are often referred to as *non-assembly mechanisms*, a term introduced first early in the 21st century [1].

Over the last two decades, many research groups have approached this problem by adopting additive manufacturing (AM) techniques, which are also referred to as 3D printing techniques, as the most feasible solution. This manufacturing method creates 3D constructions through sequential addition of material in a layer-by-layer [2] approach. The advantages of this method are numerous, but most importantly, it enables the fabrication of structures with complex geometries regardless of any specialized manufacturing skill or labor demanding procedures. The versatility of AM techniques is the core motivation for a thorough change in the current way of designing and constructing complex mechanisms.

In fact, it has been pointed out that multi-articulated mechanisms whose main specific function is that of mechanical motion could be built directly with satisfactory precision using current AM technologies without requiring any post-assembly [3]. Furthermore, several groups have already achieved successful fabrication of non-assembly mechanisms with different AM techniques. Joints were fabricated from polymer [1,4,5] and metallic [6–8] materials, soft robots were produced with flexible materials and fluids [9,10] and fully assembled actuators were conceived with more elaborated AM-based techniques [11]. Overall, the mechanisms were successfully created with good kinematic characteristics and satisfactory performance.

Despite the existence of several examples of successful non-assembly fabrication with 3D-printing, a comprehensive analysis on the design and manufacturing of such examples shows several limitations brought by the operational principles of each AM technique during the fabrication process. The spectrum of achievable mechanisms complexity is consequently restricted.

An alternative approach for non-assembly fabrication lies on a promising technology based on AM often termed as hybrid or multi-process 3D-printing. Parts can be produced not only in a non-assembly approach but also with increased functionality by using AM in

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Fig. 1. Rolling toothed joint fabricated by AM.

combination with complementary processes (such as machining, manual embedding of parts, direct printing of electronic components and more) [12]. Especially when referring to non-assembly fabrication of mechanical parts, some of those complementary manufacturing procedures could hold an equivalent or even higher level of complexity as compared to traditional manufacturing techniques because automation has not been fully achieved and additional skilled human involvement is still necessary [13,14]. Considering also the underlying limitations of AM, it is crucial to thoroughly understand each 3D-printing technique to fully exploit their potential and to reduce their shortcomings, in order to understand what level of mechanism complexity can be reached with single step fabrication.

The purpose of this manuscript is to review the applications of AM techniques in the construction of non-assembly mechanical parts and to discuss the challenges involved, thus providing perspective regarding the advantages and limitations of current AM techniques in the production of complex mechanisms. This paper focuses on the conception of multi-body mechanical assemblies at the macro-scale. Single step fabrication of structural electronics and microelectromechanical systems (MEMS) are, for example, not covered here, as they are reviewed elsewhere [12,15,16].

2. Background on additive manufacturing (AM) processes and joints

2.1. AMprocesses

AM allows for fabrication of models from three-dimensional computer-aided designs (CAD) by sequentially adding layers of material [2]. At present, AM techniques are classified in seven groups according to the ASTM standards [17]. These groups differ from each other in the way the layers are created and the way the layers are bonded to each other. *Vat photopolymerization* processes use liquid photo-curable resins that react to ultraviolet radiation (UV) and become solid after a chemical reaction. The most common technique is known as stereolithography (SL) [18]. *Powder Bed Fusion (PBF)* process uses energy to generate fusion of particulate material, a methodology to control the fusion of particulate material over a predefined track in every layer, as well as components destined to smooth and add new particulate layers [19]. PBF often requires no support structures, because unused polymeric powder serves as a support basis for overhang structures. In contrast, support structures may be still needed during metallic PBF fabrication to prevent excessive warping due to high residual stresses [20]. *Material extrusion* process uses pressure (and high temperature) to force the material through a nozzle in a semi-solid state. The most widely known material extrusion technology is the fused deposition modelling (FDM™) [21]. *Material jetting (MJ)* process uses specialized nozzles to deposit drops of liquid material over a building platform. The new layer is then solidified commonly by UV light and moved downwards. In many cases, more than one jetting head is used, enabling deposition of support material and different part materials simultaneously. Support structures could be removed using a chemical agent such as sodium hydroxide solution or with water jet [22]. *Binder Jetting (BJ)* process ejects binder droplets over a powder bed to form spherical agglomerates and bond them to the previous layer [23]. *Sheet lamination* processes use a laser to cut de shape of each cross-sectional layer out of a paper material sheet. Each new layer is then bonded to the previous layer via chemical compounds, clamping mechanisms, heat, or ultrasonic welding [24]. *Directed energy deposition (DED)* process uses an energy source to melt material, which is being deposited onto the building platform. After the material is fixed and solidified, a new layer is deposited on top [25].

2.2. Mechanical joints

AM principles permit the construction of complex geometries in a single step, thereby removing the need for skilled technical personnel and labor-intensive procedures. Streamlining of the manufacturing process may therefore be possible through proper adjustment of the fabrication process of basic elements, i.e. links and joints. Joints, as a means of constraining the number of degrees of freedom (DoF), often play a central role in the function of mechanisms and deserve special attention, because their successful production often necessitate precisely-controlled geometric dimensions. Two separate groups, traditional rigid-body joints and compliant joints, have been considered here to review the joints fabricated with AM. Joints like the rolling toothed geometry shown in Fig. 1 are examples of precise fabrication that could be achieved with AM. Further background on joint concepts and a classification based on working principles and DoF can be found in reference [26].

3. Rigid-body joints

Traditional link connections in a mechanism are accomplished by placing rigid bodies between two or more of its elements. These joints generally comprise multiple bodies and are required to restrain specific DoF's without deforming. Successful joint performance is therefore highly dependent on the surface quality of parts and the clearance between bodies. Strict geometrical dimensions and a proper surface finish reduce backlash and friction, both major concerns in the design and manufacturing of mechanisms. Hence, high accuracy is critical for fabrication of rigid-body joints with AM. Moreover, the use of support structures is an issue, because (1) removal procedures that generally deteriorate the surface quality of parts are usually necessary and (2) purge areas are sometimes required when trapped material is difficult to reach. For high-end joint manufacturing, AM should provide high accuracy of features and reduced layer thickness during fabrication, no or easy-to-remove support material, and easy cleaning of residual material when needed. Studies introducing non-assembly fabrication of these rigid and multi-bodied joints are grouped by the AM process employed and are presented next.

3.1. Vat photopolymerization

Single step fabrication of joints using the vat photopolymerization process has been reported with the SL technique using an SLA 190 machine with a Cibatool® SL 5170 resin. The fabrication process was adjusted through a trial-and-error approach by changing different manufacturing parameters such as clearance, size, and support structures. The clearances were optimized by sequentially fabricating joints with initial clearances of 1 mm which were reduced by 0.1 mm in every subsequent step until the joint stopped to work properly. Afterwards, the clearance was raised by 0.05 mm in new steps until a smooth motion was again present in the joint. Optimal clearances were found to be 0.5 mm for circular surfaces and 0.3 mm for planar surfaces. These clearances guaranteed smooth joint mobility made possible through sufficient surface quality while avoiding blockage that may be caused by support structures inserted between the surfaces. Revolute, prismatic, spherical, and universal joints were fabricated as shown in Fig. 2a–d [1].

3.2. Powder bed fusion (PBF)

3.2.1. Polymer PBF

Non-assembly fabrication of joints using PBF was achieved first by Mavroidis et al. [1] using the SLS technique. A Sinterstation 2000 machine (DTM Corporation, Austin, TX) was used for that purpose. Based on their previous experience with SL technique and taking into consideration that the Sinterstation 2000 machine had better accuracy, similar clearances were stablished (0.5 mm for spherical surfaces and 0.3 mm for planar surfaces). Revolute and spherical joints were successfully fabricated as shown in Fig. 2a and c.

Modified spherical joints were also fabricated following a better residual extraction principle [4]. After experimenting with different concept designs, a cage-in-socket design (Fig. 2e) was adopted. This design was created specifically to present friction between the parts. This was achieved by introducing gaps between the surface of the socket and the cage to prevent the parts from joining during fabrication. To find suitable parameters for this design, different features were put to test including gap distance and size. The different sets of joints were built using the SLS technique (EOS FORMIGA P 100 machine). The minimum gap achieved before the parts fused together was 0.3 mm. Additionally, the authors reported that residuary material was easier to reach and remove due to the cage-shaped design.

3.2.2. Metallic PBF

Metallic non-assembly mechanisms are highly desirable, because their high mechanical properties expand the range of possible engineering applications. Assemblies fabricated with AM from metallic materials can withstand higher loads as compared to polymeric assemblies.

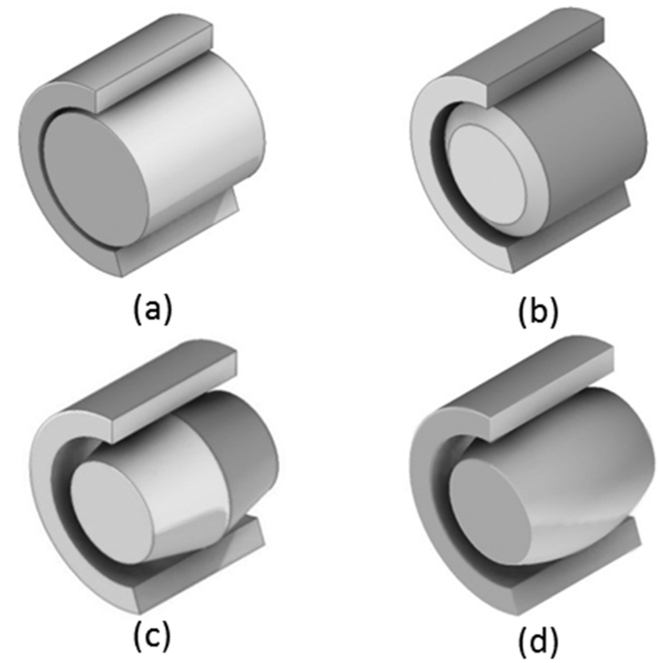

Fig. 3. Pin joint concept designs considered for non-assembly fabrication (a) traditional pin (b) with chamfered ends (c) Double cone (d) Drum-shaped [7].

Since a large joint clearance could lead to vibration and instability, new design concepts have been introduced to reduce the minimum clearance achievable in pin joints. Three new alternatives are presented in Fig. 3b–d. Stress analyses were carried out to explore the mechanical behavior of alternative joints [7]. It was found that the drum-shape configuration shown in Fig. 3d exhibited the best mechanical performance. Furthermore, based on the perception of reduced joint functionality due to residuary stuck material between clearances, the drum-shaped joint was claimed to allow easy support cleaning. Grounded on these findings, fully working drum-shaped pin joints were fabricated by SLM technique in universal joint configurations [7]. This pin design makes use of the wider space in the outer ends as purge areas, thus allowing a reduction of the clearance in the center of the joint. Pins were built using a Dimetal 280 machine with 316L stainless steel, achieving minimum operating joint clearances of 0.2 mm [3], 0.3 mm [7] and 0.1 mm [8]. In addition, different conclusions were drawn after completion of different experiments regarding the processability of the SLM technique for non-assembly mechanism fabrication [27,28]. Processability issues like scanning speed, extraction of residual and support materials, build direction, and critical fabrication angle were considered. Scanning speeds are directly related to the amount of energy employed to melt the metallic powder. In case of improper use of

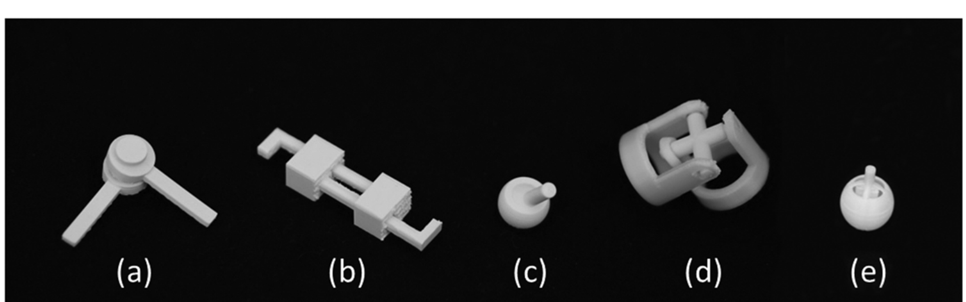

Fig. 2. Joint concept designs for AM non-assembly fabrication. (a) Revolute joint [1], (b) Prismatic joint [1] (c) Spherical joint [1], (d) Universal joint [1] and (e) Cage-in-socket joint [4].

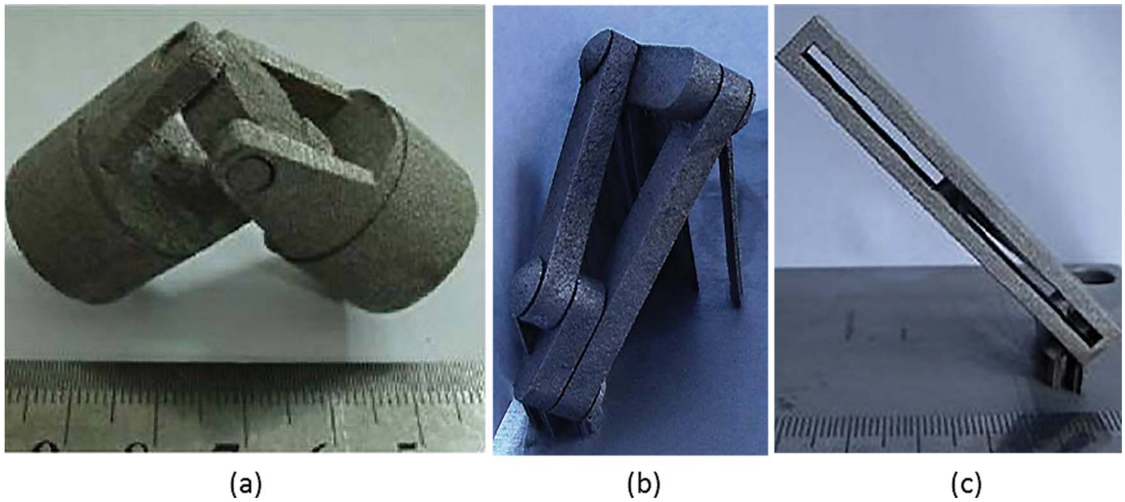

Fig. 4. Non-assembly joint samples fabricated in stainless steel material using metallic PBF processes. (a) Universal joint, (b) crank rocker mechanism [8] and (c) rocker-slider mechanism [27].

energy, the transmission of heat could melt the powder inside the clearances, thus sticking residuary material to the surfaces. The minimum joint clearance achievable is therefore dependent on the particle size of the powder and the quantity of the employed laser energy [3,28]. As previously mentioned, even though the SLM technique is a powder-based technology, support structures may still be needed when facing overhang fabrication. These structures are generally undesired, because the extraction procedure normally deteriorates the surface [3]. Moreover, support structures are difficult to reach when they are inserted inside the clearances, consequently compromising the surface quality and the functionality of the mechanisms. Nevertheless, avoiding the insertion of support structures inside the clearances is often possible through proper choice of process parameters, i.e. fabrication direction, scanning speed, particle size, etc., which enable suitable critical fabrication angles [27,28]. Universal joints (Fig. 4a), a crank rocker mechanism (Fig. 4b) [8], a rocker- slider mechanism (Fig. 4c) [27] and an abacus [29] were successfully built using modified fabrication directions and proper process parameters. A correct selection of processing strategies could be used to avoid the insertion of support structures inside the clearances.

Alternative joint designs have been also built from aluminum and titanium alloys using a DMLS machine (EOSINT M270 Xtended version) [6]. Concave and convex shapes were adopted for the pin joints using well-defined curvatures as self-supporting structures. Optimal process parameters for the highest density and best surface quality of parts fabricated with aluminum alloys had been stablished in previous investigations [30,31]. These parameters were used to fabricate the simple gear train mechanism with concave-shaped pins and concave-shaped hole joints from an aluminum alloy (Fig. 5). Alternatively, default machine parameters were used to fabricate a simple joint with a convex-shaped pin and a concave-shaped hole joint from a titanium alloy (Fig. 5). Aluminum parts exhibited smooth mobility at a minimum joint clearance of 0.1 mm, while titanium parts achieved the same at a minimum joint clearance of 0.08 mm.

3.3. Material jetting (MJ)

As previously mentioned, drum-shaped designs for pin joints can reduce the achievable clearance in non-assembly joints [7]. To validate this new concept, several universal joints were fabricated with conventional pins and drum-shaped pins with an MJ process. An Objet (2010) Eden 350 V machine was used with two different materials (Fullcure 720 and VeroWhite) for that purpose. The constructs achieved 0.2 mm of minimum clearance for the conventional joint and 0.1 mm of minimum clearance for the drum-shaped joint [32]. In a study by Calì et al. [4], modified spherical joints were also fabricated using MJ. Likewise, a cage-in-socket design was adopted and different sets of joints were built using an Objet Polyjet machine following the same methodology used for the polymer PBF technique. The authors reported identical results as the experiments involving the SLS technique, i.e. a minimum gap of 0.3 mm and the easier cleaning of residuary material and support structures.

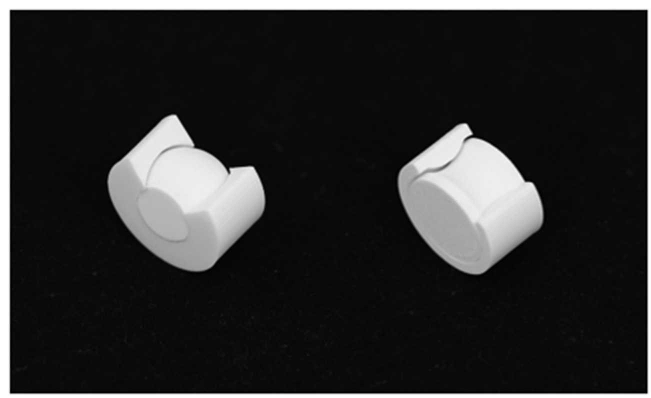

Fig. 5. Non-assembly joint concepts for AM in aluminum and titanium alloy [6].

3.4. Material extrusion

A recent work by Wei et al. [33] assessed the performance of new joint designs based on drum-shaped and cylindrical-shaped revolute joints. A new worm-shaped design was fabricated with a Stratasys Vantage™ machine using ABS material and dissolvable supports. The worm-shaped joint showed significant dynamical improvements compared to other non-assembly joint designs as it achieved a minimum joint clearance of 0.05 mm. Even though no other rigorous research was found regarding non-assembly fabrication of rigid-body joints via Material Extrusion based technologies, online hobbyist community of entry-level FDM™ users have shown successful production of revolute joints reaching a minimum clearance of 0.3 mm [34]. Although Material Extrusion based processes are commonly perceived to be the less precise of main commercially available AM techniques, recent developments have reached reasonable part accuracy levels and also dual deposition of part and soluble support material. As shown by [33], industrial-grade FDM™ 3D printers could equate other AM technologies in terms of minimum achievable clearance when building non-assembly

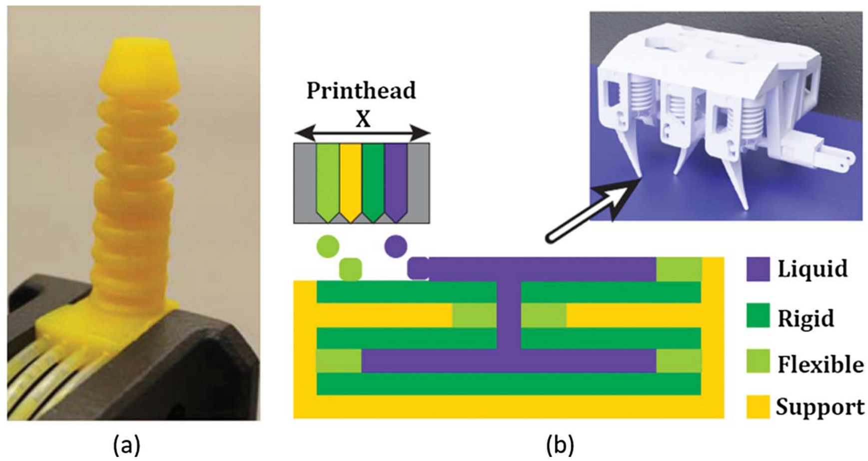

Fig. 6. Soft robots produced by AM single step fabrication (a) soft actuator with pleated structure [10], (b) Scheme showing deposition of liquid and solid materials in parallel to create the bellows structure in a six-legged robot [9].

joints.

The high versatility and easy accessibility makes the Material Extrusion technology a valuable choice for prototyping non-assembly constructs especially in settings where high-end technology is out of reach. To explore the full potential of new Material Extrusion technologies into the non-assembly rigid-body joint framework, additional research is required.

4. Compliant joints

Compliant joints allow the relative motion of elements through deformation of elastic members. Manufactured as a continuous and flexible body, these joints compose an interesting alternative for fabrication of non-assembly mechanisms with AM techniques, because there is no presence of joint clearance between links. Successful performances are therefore not affected by the lack of high precision manufacturing. Instead, the building materials and geometric configurations compose the most important features determining the mechanical performance of such joints. Since AM allows practically full geometric freedom, the key drawback lies in the mechanical properties of the building materials. Although acceptable elastic behavior of building materials is basically present with all AM techniques, precise mechanical properties, like elastic modulus or yield strength, are difficult to predict and should be also provided to enable AM of complaint joints for high-end applications.

To accomplish different types of motion, several compliant shapes have been fabricated with AM techniques. Flexural hinge-type joints were created with SLS [35] and Material Extrusion [36,37] technologies. A translational joint [38] and a trispiral joint [39] were made with FDM™, while twist compliant mechanisms have been produced using SLA [40], and lattice flexures have been fabricated from titanium using the electron beam melting technique [41]. Further complexity has been achieved using a MJ-based Polyjet (Stratasys) process by fabricating multi-material compliant joints. A helical-shaped compliant joint [42] and a compliant force-inverter [43] were conceived using multiple phases of rigid and soft materials, thus providing stiff structural parts to hold the construct as a robust entity and localized flexible points. AM techniques were also used to provide solutions for stability and parasitic motion, both major concerns in the design of compliant joints. The addition of multiple joints and links in parallel layers was successfully assessed and supplementary guidelines for compliant joints designs were proposed for correct performance of compliant mechanisms [44].

5. Advanced non-assembly mechanisms

Arrangements of multiple joint and link elements compose the basic structure of several robots and actuators. Such arrangements have also been fabricated with AM technologies in a single step and are presented in this section as advanced mechanisms.

Successful fabrication of an advanced mechanism consisting of traditional rigid-body links and joints in a single step with AM technologies is reported by Wei et al. [11]. The MJ Polyjet technique was employed in order to build a pneumatic robot. An Objet Eden 350 V machine was used with the VeroClear 950 as main building material. Although parts were conceived completely assembled in a single step, the clearance achieved between movable parts affected deeply the transmission efficiency of the mechanism. The final construct eventually showed instability, vibration, and inaccuracy after performance tests.

Further development on compliant mechanisms allowed the formation of alternative advanced mechanisms. Inspired by biological systems, soft robotics have recently gained important attention and have been extensively studied over the last decade [45]. Fabricated out of compliant materials, these robots are safer for human interaction, could move in a large number of degrees-of-freedom and have the potential to adapt their shape to the environment [46]. Despite the advantages of soft robotics, manufacturing and conception of these devices is still challenging. Even though several manufacturing techniques have been used [47], design concepts have a tendency towards more complex geometric features [48], thereby demanding challenging fabrication procedures. Moreover, embedded components are usually included into the designs due to the actuation principles employed, thus contributing with additional complexity to the fabrication. Since many AM techniques are compatible with soft material and due to the aforementioned capability of producing complex geometries, AM has been proposed as a suitable process to create fully working soft robotics. Although several soft robotic examples produced via AM techniques could be found in the literature [49,50], they still require manual post-processing steps. Overall, research regarding single step fabrication of soft robotics and actuators is very limited and scarce. Two examples are presented next.

An actuator inspired by the tentacle muscle of octopus was fabricated using an SL-based technique. The Digital Mask Projection Stereolithography (DMP–SL) technique was employed, because it allowed photopolymerization of a whole layer in a single step. The complex pleated structure shown in Fig. 6a was fabricated using the commercial Spot-e resin (Spot-A Materials, Inc.). Each air inlet is connected directly to one chamber allowing pressure differentials between two opposing cavities. The actuator bends when pleated structures on one side expand and the opposing side contracts. Multiple 3d trajectories were achieved at a reasonable speed (< 70 ms) [10].

An alternative approach embraced the option of printing both fluids

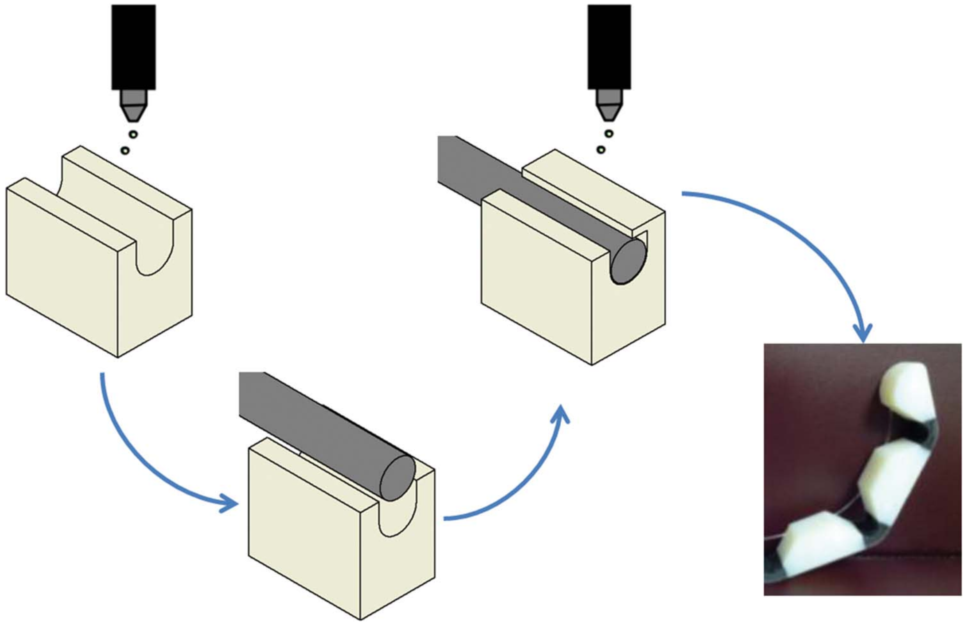

Fig. 7. Embedding scheme of SMA fibers [14].

and solids in parallel. By tricking a commercial MJ machine (Stratasys Objet260) control system, certain fluids could be deposited along with photocurable resins. A list of design rules was created after iteratively manufacturing different geometries in different directions. Different hydraulic robots were conceived encasing the fluid with soft photocurable material. A six-legged robot was built enclosing fluid into bellows structures as shown in Fig. 6b. The bellows structures exert force by applying pressure differentials into the fluid via an electric motor. Likewise, a fully housed gear pump and a soft gripper were successfully fabricated in a single step following the abovementioned design rules [9].

Even tough fully working soft robotics were conceived, current building materials are very limited and provide poor mechanical properties. For both SL and MJ techniques, the authors reported insufficient fatigue lifetime, specifically tears appearing after continuous actuation [10]. Alternative options for single step fabrication of soft robotics includes direct deposition of soft actuators, i.e. smart materials that activate and bend with different stimuli (e.g. heat, magnetism, light, moisture, pH, electricity). Additional literature on non-assembly AM soft actuators can be found in [51].

6. Non-assembly advanced mechanisms with embedded components

Embedding of different components (either manually or in combination with other manufacturing procedures) during AM fabrication of parts has become a technique increasingly used in recent years. In this review the applications of the embedding techniques facilitating fabrication of non-assembly mechanical parts are shown. We also provide some examples of embedded electronics. More information on the embedding of electronics can be found in [12].

One of the many advantages of AM is the possibility to access the internal geometry of manufactured parts and incorporate functional components during their fabrication. Embedded components during a layer-based fabrication could be traced back to the early 90s, where they were used as fundamental parts of electromechanical devices. This embedding process was more extensively used after the introduction of the technique referred to as shape deposition manufacturing (SDM) [52]. These techniques not only deposit material onto a layer but also use computer numerically controlled (CNC) machining to precisely define the surface of the part by removing material. The CNC machining step could be used to define cavities in which different components may be inserted. The deposition of layers could be resumed on top of the inserts to fully encase the components. SDM has been used for embedding pneumatic actuators, servo motors, and flexible inserts to create insect-like robots [53,54], fibers and electrical wires to create flexible mechanisms [55], and sensors for measuring and monitoring purposes [56–60]. Although the outcome has been successful, the SDM process is still laborious, slow, and limited to a small spectrum of materials [61].

SL has been also used to embed different components during the fabrication of mechanisms. Initially used to embed sensors [62], the SL technique has proved to be a suitable procedure to embed other types of components. Procedure recommendations were stablished after successfully embedding screwdrivers, electric motors, gears, nuts, and screws [63]. Fabrication issues like laser shadowing, support structures, and recoating of vat have been reported and addressed. Different strategies such as the inclusion of shape converters were introduced and subsequently taken into consideration for successful fabrication of a radio-controlled vehicle [5], a robotic hand [64], a fan and encased joints [65]. Despite the fact that successful mechanisms were produced, real-world applications are very limited due to the arduous work implicit when trying to circumvent the aforementioned problems and the lack of compatible materials with the SL technique. Different electronic components have been also extensively embedded for the past decade using manual operations and/or extra manufacturing processes (e.g. [66,67]). A comprehensive study on the SL technique and the different techniques for embedding electronics can be found in [68].

MJ process, and more specifically the Stratasys Polyjet process, has been used to embed electronics [69] and more recently SMA actuators [14,70]. SMA fibers were embedded (Fig. 7) to conceive active compliant finger and knee. A multi-material Polyjet machine was used for fabricating rigid parts with VeroWhite material and flexible parts with TangoBlack material. Guideline procedures for successful embedding and anchoring of SMA fibers have been established [14]. Further work established additional guidelines for embedding and fixing SMA fibers and springs into more complex configurations. Using a clever cavity design a compliant construct with embedded spring SMA actuators was produced. Likewise, the VeroWhite material was used for the rigid parts and the TangoBlack was used for the flexible parts [70].

Material extrusion based technologies have been the mostly used techniques to embed different electronic components such as sensors

[71], functional circuits [72,73], transmission lines [74] and more. In addition, successful non-assembly fabrication of a multi-articulated electromechanical device has been achieved. Aguilera et al. [13] created a rotational motor by manually embedding magnets, electromagnets, bearings and an electronic speed controller into the thermoplastic substrate delivered by AM technology. The material extrusion process was stopped in five stages, in where different components where manually inserted, and subsequently resumed on top in order to fully encase all parts.

7. Discussion

7.1. Rigid-body joints

The review of literature shows several examples of mechanisms fabricated using AM without any need for manual post-assembly. Throughout this search, the MJ-based Polyjet technique was found to be the most widely used AM process for the fabrication of non-assembly mechanisms. Both compliant and traditional mechanisms were successfully conceived achieving reasonable levels of (geometrical) complexity. The remarkable feature of some 3D printer (e.g. Objet, Stratasys) for parallel deposition of part and support material has proven to be significantly advantageous over other AM fabrication principles. Nevertheless, complex internal structures are more challenging to fabricate, because purge connections must be taken into consideration for support removal of encased constructs. Clever deposition of fluid and support material (in parallel with part material) circumvents this problem when fabricating actuators for hydraulic applications. Parts could be fabricated surrounded by a small layer of liquid, thus preventing the fusion of material part with the inner walls of the casing and fragile support structures. As in MacCurdy et al. [9] pump design, liquid and support material may be removed as normal mechanism actuation is executed.

Although PBF process is also recognized to facilitate overhang fabrication, extraction of the residual material is still challenging and could strongly influence the performance of the fabricated joints. Trapped powder inside joint clearances could lead to high friction and poor mechanical performance. As with the Objet Polyjet technology, purge openings and connections must be taken into consideration for encased mechanisms and tight clearances. Moreover, and in addition to the typical “staircase effect” of every AM technique, final surface roughness of parts is still difficult to control and mostly unsuitable for high-precision applications. Related research has studied the effect of different fabrication parameters on the final surface roughness of polymeric [75] and metallic [30] parts. Despite previous research, high-end surface quality remains uniquely achievable through additional post processing steps.

The addition of support structures in metallic PBF techniques is a limiting factor, because arduous post processing removal steps are unavoidable and their extraction contributes to a poor surface quality. Fortunately, evidence of successful evasion of support structures has been shown and is possible by providing proper critical fabrication angles. This could be achieved by adjusting the fabrication parameters to their optimum values and choosing the appropriate build direction.

Despite early introduction of the vat photopolymerization processes to the development of non-assembly mechanisms, this type of processes was rarely used in further investigations of traditional joint fabrication. As previously shown, clearances achieved in jointed structures by this technique are inferior and the addition of support structures may be problematic. However, different alternatives to the SL technique, like the DMP-SL, and further developments on photocurable materials are promising options for fast conception of robust soft robotics and compliant mechanisms.

7.2. Compliant joints

Application of compliant mechanisms is highly advantageous in the context of manufacturing, because joint clearance between links does not exist. Still, when it comes to fabrication by AM techniques, material selection presents a major limitation. Many available materials are unsuited for large deformation applications. Furthermore the effect of multiple printing parameters in the compliant behavior of parts has not been studied thoroughly. Even though satisfactory kinematic performances have been achieved [36,39], little attention has been paid to the kinetics of the joints. For instance, there is little information in literature on the stiffness of joints. To reach an optimal mechanical performance, the mechanical behavior of joints should be studied further, for example with a setup to determine the stiffness of material extrusion based flexure hinges [37,76]. An alternative to the limited number of available flexible materials that can be processed with AM techniques is the use of multi-material deposition and new topology optimization algorithms which could significantly improve the mechanical behavior of compliant bodies by increasing deformation limits of crucial parts before failure [43].

Furthermore, the design freedom of complex geometries permits the manipulation of the inertial and stiffness properties of 3D printed parts, thereby allowing enhanced compliancy of joints. Careful design choices must be taken in order to achieve consistent stiffness over active and inactive axis with the aim of allowing flexural motion while preventing parasitic motion of compliant parts. Detailed stiffness analyses on numerous compliant designs can be found in [77]. Even though several compliant shapes have been proposed both in polymeric and metallic parts so far, there exist more joint type possibilities that could be fabricated with AM and could potentially be more suited for certain mechanical applications.

7.3. Embedding of external components

Embedding of several components during AM fabrication has proven to enhance mechanical properties and increase the features of the fabricated parts. Parts could be produced with new features by adding sensors, actuators, joints, links, and smart materials during the fabrication process. The embedding processes have the potential to create advanced mechanisms without any post-processing requirements. Nevertheless, the design processes need to take into consideration the correct positioning and encasing of embedded parts. Furthermore, careful monitoring of fabrication processes may be needed for just-in-time pausing of the manufacturing process, manual insertion of the embedded parts, and resuming the production process. Overall, the embedding process requires skilled manual operations and time-consuming procedures to achieve successful performances. The concomitant complexity during fabrication is therefore presenting difficulties and needs further assessment.

7.4. Final remarks and future directions

We envision a new paradigm of manufacturing of mechanisms. Fully working mechanisms could be fabricated in a single step without any requirement for post-manufacturing assembly. By replacing the traditional manufacturing process with AM, robust assemblies could be produced on-demand and *in situ*, thereby eliminating several logistic problems. Customized devices could be produced for any kind of engineering applications. For example, patient-specific surgical instruments could be fabricated as a disposable medical device while prosthetics and orthotics may be produced in different settings without the need for a well-equipped workshop or laboratory.

Current technologies, however, lack sufficient versatility for fabrication of fully-assembled and multi-articulated complex mechanisms. Accurate joint clearances with satisfactory surface roughness are still difficult to achieve, encased complex features require purge channels or elaborated strategies for support removal, available materials are still limited and lack sufficient mechanical performance and embedding techniques require complex and demanding processing steps. Yet, clever use of multi-material AM techniques could combine rigid and soft materials to create both structural parts and compliant joints. Multi-material AM requires compatibility of building substances and their corresponding printing processes, thus limiting the range of suitable materials that can be combined in a single printing job. Physical and chemical properties of building materials (like Van der Waals forces, thermal expansion, etc.), as well as printing parameters (like material delivery system, processing temperature, etc.) constrain interlayer bonding and hence, printing feasibility [78]. However, clear examples of dual deposition of polymers with rigid and soft characteristics into mechanical parts have been demonstrated using MJ based technologies. Due to the physics of material deposition into the building platform by processes like MJ or Material Extrusion, multi-material AM is accomplished by adding multiple nozzles, as found in commercially available equipment, loaded with materials capable of compatible bonding. Other than materials used for the PolyJet (Stratasys) technology, no material combinations suitable for multi-material AM have achieved desired mechanical behavior for both structural and compliant parts. Bonding of rigid and soft materials with sufficient position accuracy is a main concern that should be addressed in order to expand the range of compliant and rigid non-assembly constructs achieved by multi-material AM. Other processes, such as SL or SLS, require more elaborated techniques and present a limited variety of compatible materials. Therefore, they have not been used to fabricate either compliant or rigid-body assemblies with multi-material AM. Additional combinations of dissimilar materials could be processed in a single printing job by using hybrid 3D-printing in where different AM and other manufacturing techniques can be combined [12]. As an example, Lopes et al. [66] deposited metallic particulate material using Direct Printing (DP) onto polymeric substrates created by SL. Although encouraging, such hybrid 3D-printing approach has not processed rigid and soft materials into a composite resulting in a multi-articulated mechanism. Current compatible materials processed by hybrid 3D-printing lack sufficient mechanical properties to manufacture successful articulated assemblies and need further development.

Depending on the ultimate use, correct design of compliant joints could smartly replace traditional joints, eliminating the tight tolerance requirements. Certainly, further development on the field of design for additive manufacturing could set the stage for increasing the complexity achievable in non-assembly fabrication [79,80]. New emerging research fields that may be potentially embraced by this non-assembly fabrication framework contemplate direct deposition of smart materials into structural parts [51], self-assembly of components using bonding forces [81], shape-shifting of 2D structures into 3D structures [82] and control of mechanical properties in localized areas of monolithic structures via meta-material design [83].

8. Conclusion

There is no doubt that the progress in AM has allowed for considerable design freedom and is a promising opportunity for the development of non-assembly fabrication. Still, AM is several steps away from replacing current assembly lines of traditional manufacturing. Assemblies produced in a single step by AM exhibit different shortcomings depending on the process employed. In general, important shortcomings found in current non-assembly mechanisms produced by AM are backlash, poor surface quality, weak mechanical properties (fatigue life, strength, toughness, etc.), and stuck support or/and residual material. Amongst all the limitations of manufacturing with AM, the need for overhang structures, limited range of building materials, inadequate fabrication accuracy stand out as the major drawbacks and are critical for further development of high-complexity fabrication of assemblies in a single step.

AM, nevertheless, has some unique characteristics that could potentially shift the current manufacturing practices to non-assembly paradigms. Given that AM processes could be used to fabricate shapes that would be impossible to manufacture with other manufacturing techniques, new design approaches could be used, leading to availability of parts that achieve equal or even higher performance than traditionally-assembled mechanisms. Alternative designs of monolithic compliant mechanisms that could replace traditional rigid-body joints is just one such example. Further development of the materials that could be processed with AM may also improve the mechanical properties of parts and stablish new damage-free pathways to remove support structures. New emerging techniques for AM, like meta-material design, could also be introduced to facilitate non-assembly fabrication of high complexity parts and should be further implemented to recognize their full potential.

Disclosure

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