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A state-of-the-art review

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DOI
10.1016/j.addma.2021.101846

Publication date
2021

Document Version
Final published version

Published in
Additive Manufacturing

Additive Manufacturing 39 (2021) 101846

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Review

Design of non-assembly mechanisms: A state-of-the-art review

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ARTICLE INFO

Keywords:
Additive manufacturing
3D printing
Non-assembly mechanisms
Design
Review

ABSTRACT

Additive Manufacturing (AM) or 3D printing has enabled the production of increasingly complex parts that are difficult to produce with conventional manufacturing methods. Its additive nature has made it possible to create interlocking parts in a single production step. This creates opportunities for new ways of designing and producing mechanisms, which do not need to be assembled after production, called non-assembly mechanisms. Non-assembly mechanisms are different from traditional mechanisms, since they show an unprecedented integration between geometry, material and structure. In this review, by means of a systematic literature search the current state-of-the-art of non-assembly mechanisms is reviewed and analyzed based on the challenges encountered in their design and production. The found examples were categorized according to types of mechanism that have similar production considerations. Per category is discussed what the challenges and opportunities are for the design of non-assembly mechanisms. This review aims to provide a helpful overview of best-practice examples that can be used as inspiration for further development of innovative non-assembly mechanisms.

1. Introduction

Additive Manufacturing (AM) or 3D printing is changing the way products are designed and manufactured. Recent developments in the quality and resolution of 3D printers have made AM a viable production method for parts and products, instead of only being used for prototyping. This has led to an increased interest in using AM for the production of functional assemblies.

Traditionally, most products can be seen as a collection of individually fabricated parts, which are subsequently assembled into a working product. The assembly step can take up a lot of time and costs. Improvements to this step can be made by designing parts optimized for assembly [1]. AM offers opportunities in this respect because no compromises have to be made to simplify parts for assembly, instead they can be optimized for their function, provided they take the design considerations for the specific AM process into account [2].

Two of the most common ways in which AM can contribute to the design of mechanical assemblies, is by considering an assembly as a collection of parts that either form 1) a rigid structure or 2) a movable mechanism [1]. In the case of a rigid structure, assembly is necessary because there is no efficient way to produce it as a whole, for instance due to limitations in materials, production techniques or costs. Although they consist of separate parts, they require stiffness and rigidity between the part connections [1]. For example, a table can be seen as a structural assembly, since the table top and the legs are often produced separately, consisting of different materials and made with different production processes. However, the end result functions as one product. The shape complexity offered by AM can eliminate some of these production limitations by combining multiple, separate parts, into one complex-shaped part; resulting in a reduction of the number of components [3,4]. This process is known as “part consolidation”, for which numerous design guidelines exist [3–8].

Moveable mechanisms, on the other hand, require assembling of multiple parts because there is a need for movement between the parts [1]. Traditionally, this has been achieved by separately fabricating parts with carefully measured out tolerances, and subsequently assembling them into a mechanism. AM has also brought new possibilities for the production of movable mechanisms. There are three different ways to produce movable mechanisms by AM. First, using a traditional approach, in which separate components are produced and afterwards assembled, resulting in the same workflow as for mechanisms produced by conventional manufacturing [9]. Second, using embedded assembly, in which one or more components, often of an electronic nature, are incorporated into the 3D printed part, while it is still being produced

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https://doi.org/10.1016/j.addma.2021.101846
Received 26 May 2020; Received in revised form 9 December 2020; Accepted 5 January 2021
Available online 9 January 2021

[10]. An example of embedded assembly is integrating batteries or motors in 3D printed robots [11,12]. Finally, in non-assembly 3D printing, fully functional assemblies or mechanisms are produced in a single production step [10,13]. These 3D printed mechanisms are functional immediately out of the 3D printer, although still some post-processing steps may be required, such as to remove support material [12,14–17].

In the past two decades, many examples of non-assembly mechanisms have appeared. Often the term non-assembly is used to refer to multi-body mechanical assemblies [10]. However, any mechanism that is manufactured without an assembly step can be considered non-assembly. This includes mechanisms which do not need to be assembled by design, such as compliant mechanisms, which are monolithic structures consisting of only one part [18]. This shows that mechanisms do not necessarily need to consist of different parts, as long as they are able to transfer or transform motion [18]. Therefore, in this paper non-assembly mechanisms include all 3D printed devices that allow motion within their system, and can be produced in a single production step.

Designing non-assembly mechanisms requires re-thinking the way we design and manufacture traditional mechanisms. Specially developed design methodologies for AM have tried to come up with design guidelines to help with this [19–21]. These methodologies are often driven by the functionality of the mechanism, which in turn leads to the geometric design, material choice and specific AM process selection [5]. For the latter, additional models have been proposed that can be helpful for designers to select the most suitable AM process for their design [22–24], or to optimize the settings of the chosen AM process with respect to factors such as dimensional accuracy and mechanical properties [25]. However, these methodologies offer little to help designers and engineers navigate the immense design space that is provided by AM [19–21]. The recent interest in producing multi-functional, complex systems that are operational straight out of the 3D printer shows that there is already a lot of knowledge to overcome the most common AM challenges. Therefore, in this review we provide an overview of the current state-of-the-art of non-assembly mechanisms, with a focus on design solutions and production considerations to create fully functional designs. We categorize and analyze the mechanisms based on the described design challenges and design opportunities.

2. Literature search method

A systematic literature search was performed using the Scopus and the Web of Knowledge databases on the topic non-assembly 3D printed mechanisms. The search query consisted of three categories of keywords:

1) related to the production method: 3D print*, additive manufactur*, rapid manufactur*;
2) related to the way of producing: non*assembl*, print-in-place, assembl* free, without assembl*, fully assembled, monolithic, compliant, direct fabrication;
3) related to the product class: mechanism*, mechanical assembly, robot*, machine, joint*, device*.

The search was limited to articles in English, with no restrictions on the subject area or date, resulting in 744 articles from both databases. After eliminating duplicates, the scientific articles were selected on a number of eligibility criteria. For the production method, AM methods were accepted that can be used on a macro-scale, this excludes lithography and direct writing methods related to the production of nanoscale sensors. Bio-printing methods were also excluded. Titles and abstract were scanned to select the articles in which a physical mechanism was created by means of non-assembly AM, and for which AM was also the intended production method. This excludes mechanisms for which 3D printing is merely the prototyping method and not the main production method. In addition, the designed mechanism itself needed to be 3D printed, not only casings or frames. From the selected articles, the references were scanned for additional relevant articles that were not found by the query. In the end, 84 articles on non-assembly mechanisms were analyzed with respect to the design and production considerations for this review.

3. Classification

The selected examples of non-assembly mechanisms span a wide range of different AM processes. Although each AM process has its own specific production guidelines, as is the case with every manufacturing process, there are a number of design considerations that are similar for all AM processes [2,26,27]. For example, maximum overhang angles, the need for support structures, and optimized build directions are all AM-specific production considerations. These will inevitably influence the design process for non-assembly mechanisms as well. Therefore, it is possible to cluster them into groups for which similar design challenges apply and similar design solutions can be used. The classification is visualized in Fig. 1. Three main categories have been distinguished that are representative for AM non-assembly mechanisms: 1) geometry-based mechanisms, 2) material-based mechanisms, and 3) pattern-based mechanisms. Geometry-based mechanisms are a group of mechanisms where the functionality of the mechanism relies foremost on the geometry of the structure, which can be accomplished by using multiple bodies, such as for traditional mechanisms, or a single body, such as for compliant mechanisms. Material-based mechanisms are a group of mechanisms in which the material is predominantly responsible for the functionality of the mechanism, making use of either a single flexible material or a flexible material combined with other (rigid) materials. Pattern-based mechanisms describe a group of mechanisms for which a pattern or repetition of a simple base unit is responsible for the functionality of the mechanism. In the following sections, examples of non-assembly mechanisms per category are discussed, focusing on the encountered design and production challenges and the identified design opportunities.

4. Geometry-based mechanisms

4.1. Multi-body

4.1.1. Design challenges

Multi-body mechanisms closely resemble the design of 'traditional' mechanisms, since they consist of separate parts. The clearances between the separate parts are challenging for most 3D print processes. Therefore, design solutions are necessary to create functional mechanisms. Table 1 summarizes the challenges for multi-body mechanisms and their proposed solutions.

Support structures are often necessary when designing multi-body mechanisms, since the bodies are separated from each other and cannot be printed in the air without support. The use of support structures has undesirable side effects: removing support material requires an extra post-processing step, the area underneath the support structures usually has a diminished surface quality, and support structures require additional material that often cannot be reused. In addition, for complex geometries it can become difficult to create sufficient room for access to remove all support structures. Therefore, to allow for removal of the support material, the geometry should be designed as open as possible [16,28,31], or specific holes for the release of support should be integrated in the design [32].

The surface finish of AM parts can be of poor quality, because of the 'staircase effect' caused by the layered print process, the relatively low resolution of 3D printers, and the presence of support material that is locally fixed to the surface. Poor surface quality can hinder the movement of joints, especially in the case of full surface contact. The 'staircase effect' can be lessened by using angular geometric shapes instead of

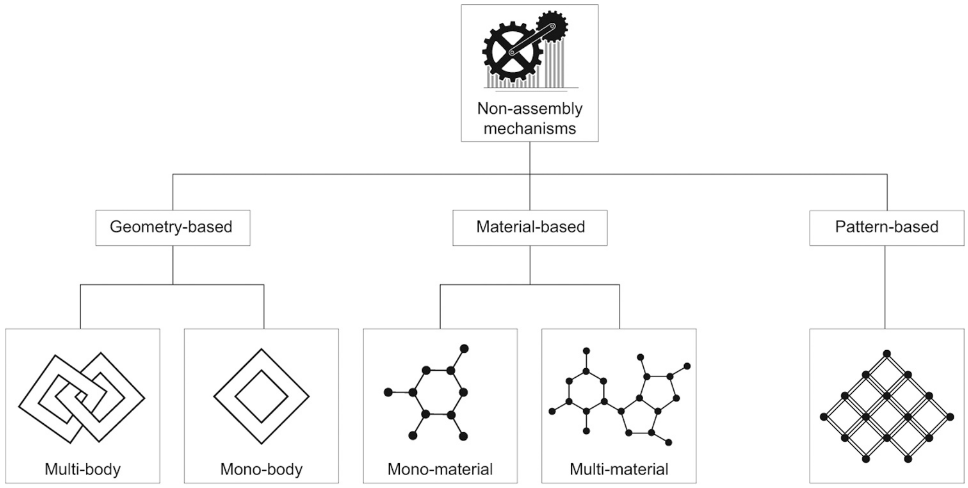

Fig. 1. Classification of non-assembly mechanisms based on groups for which similar design challenges apply. Geometry-based is a group of mechanisms where the functionality relies foremost on the geometry of the structure, material-based is a group of mechanisms in which the material is dominant for its functionality, and pattern-based is a group of mechanisms where a pattern of a simple base unit is responsible for its functionality.

Table 1
Challenges, general solutions and design solutions for the design of multi-body mechanisms, with corresponding references proposing/applying the solution.

Challenge	Solution	Design solution	Reference
Support structures	Prevent support structures	Reduce overhang angle	[17]
		Decrease clearances	[13]
	Allow support removal	Increase clearances	[16,28]
		Increase spacing between bodies	[16]
		Add features such as chamfers	[29,30]
		Use open geometry	[16,28,31]
		Add drainage/release holes	[32–34]
Surface finish	Reduce surface contact	Add protrusions/markers & dents	[29,30,32,35]
	Prevent 'staircase' effect	Reduce overhang angle	[17]
		Use angular geometric shapes in favor of organic ones	[13]
	Prevent supports	Keep interacting surfaces free from supports	[28]
	Consider the build direction	Change the build direction to suit the design	[28,29,33,34]
Clearances	Adjust geometry	Add markers and dents	[31–33,35,36]
		Change main hinge shape	[13,17,37] [32,38,39]
		Scale entire mechanism up	[16]
Strength	Adjust geometry	Optimize cross-section for the direction of movement	[28]
	Consider the build direction	Change the build direction to suit the design	[29,40]

round and organic shapes, as was illustrated by the design of a rectangular prismatic joint [13], or by reducing the angle on overhanging geometry [17]. Reducing the surface contact between moving parts by using protrusions in the surface or markers and dents can negate the effects of poor surface quality [29,30,32,35], as shown in Fig. 2. Surfaces that interact with each other should ideally be kept free from support material in order to maintain the best possible surface finish [28]. In addition, rolling joints are less sensitive to poor surface finish as compared to sliding joints [28].

A small clearance can make a mechanism more accurate, but it might cause parts to fuse together while printing. A larger clearance can lead to less accurate movement in the final mechanism [37,41]. By changing the geometry of adjacent surfaces, it is possible to obtain the advantages of minimal clearances while preventing complete fusion. Adding markers and dents to moving surfaces is a successful strategy [31,32,35,36]. In this case, the clearance can be chosen slightly smaller than the minimum clearance needed to prevent fusion. After the markers and dents fuse while printing, there is only a small overlap of material which can easily be broken apart, Fig. 2. Since the minimal clearance is a fixed value per AM process, Jansen et al. [16] noted that by scaling the entire mechanism up, the influence of clearances will be relatively smaller. However, scaling the design of an entire mechanism will also result in scaling of the clearance between the parts. Therefore, Li et al. [41] set up a parametric design to enable scaling of revolute, prismatic, spherical and gear joints. This enabled them to scale all parts of the mechanism up or down, while making sure the clearance remained at the same minimum value given the used 3D print process. Because of the layer-wise construction of AM, parts tend to have anisotropic properties. The chosen build direction is of large influence on the resulting strength of the parts [29]. Especially for moving parts, care should be taken to choose the best build direction and cross-section in order to obtain optimum strength [28].

4.1.2. *Design opportunities*

Design guidelines and best practice examples can be useful when designing multi-body mechanisms, in order to make sure the design is attuned to the specifications of the chosen AM process. Cuellar et al. [28] give a list of ten guidelines to keep in mind when designing non-assembly mechanisms for FDM printing. Their guidelines were applied to the design of a low-cost prosthetic hand for developing countries. The mechanism in the prosthetic hand was designed with large clearances to be easily printable, but when activated by the driving force the joints automatically align (Fig. 3). This way they were able to create a functional adaptive prosthetic hand, specifically optimized for

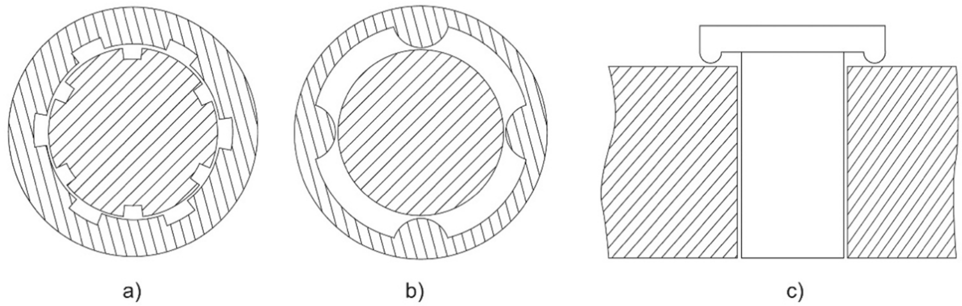

Fig. 2. Markers and dents can be added to the inside of a pin joint to obtain a smaller clearance and negate the effect of poor surface finish, by reducing the amount of surface contact.
A) Top view of a marker-dent construction within the pin-joint, adapted from [35]; b) top view of a marker-dent construction within the pin-joint, adapted from [32]; c) side view of protrusions underneath the top of the pin, adapted from [29,30].

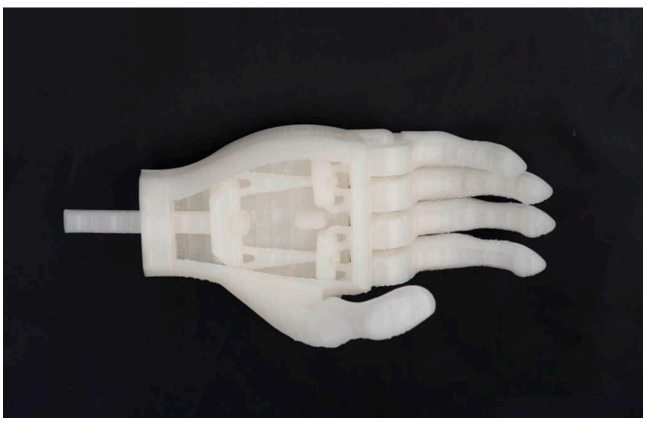

Fig. 3. Prosthetic hand with a non-assembly mechanism. Although the mechanism has large clearances, the joints automatically align because of the driving force [19].

3D printing. Sossou et al. [34] propose a design methodology, which starts from the conceptual design of the product as an input. According to them, the functional constraints should be incorporated into the design context by means of an extensive functional analysis, while keeping in mind the constraints from the AM processes. By considering clearances, printing configurations, build direction and accessibility to clearances, the position of each component and their geometry can be finalized.

The design of multi-body mechanisms often starts with the design of a single joint [13]. Best practice examples for multi-body joints include revolute joints [17,30,32,38,39,42], ball joints [13,31,36], and universal joints [29,30,37,43]. Revolute joints and universal joints both make use of pins. Altering the shape of the pin can ensure proper movement within the joint, without hindering the printability or the removal of supports.

Fig. 4 shows a number of different pin shapes that have been proposed [16,17,30,37–39]. The goal is to design the pins with minimal clearance in the joint, while simultaneously allowing for support material to be removed and preventing the joint from fusing. Adding chamfers or fillets to the edges of the joint creates as much space as possible for the removal of support material [29,30]. A drum-shaped joint (Fig. 4b) has proven a good alternative for a pin-shape [30,37,38]. The minimum clearance is determined by the widest part of the drum, which reduces instability, while leaving enough space to remove support material on both ends. 3D printed drum-shaped joints have been shown to achieve smaller clearances than regular pin joints [30], as well as more uniform stress distribution and lower stress concentrations [38]. Wei et al. [39] took the drum-shape a step further and proposed a worm-shaped joint (Fig. 4c), which showed less axial movement than the drum-shape when subjected to an asymmetrical load. A cross-shaped pin instead of a round one has been shown to facilitate in the removal of support powder, although the cross-shaped pin rotates less smoothly than the round pin [16].

Non-assembly ball joints have been designed for joints that are posable in any position [31,36,44], as shown in Fig. 5. By creating an open structure, the support powder used in the AM process can be drained. Markers and ridges were added in the ball joint to create sufficient friction for the joint to assume any pose, while simultaneously preventing fusion of the surfaces during printing.

An example of a 'joint-centered' design process was shown by Jansen et al. [16]. They redesigned a 'Strandbeest', a robotic walking mechanism, to be non-assembly 3D-printable (Fig. 6). Since they felt existing guidelines for design for AM were not sufficient for their mechanism, their process was one of trial-and-error, starting from the joints. By adjusting and testing multiple small sections of the mechanism first, they were able to optimize the design and functioning of the joints, before applying them in the complete mechanism.

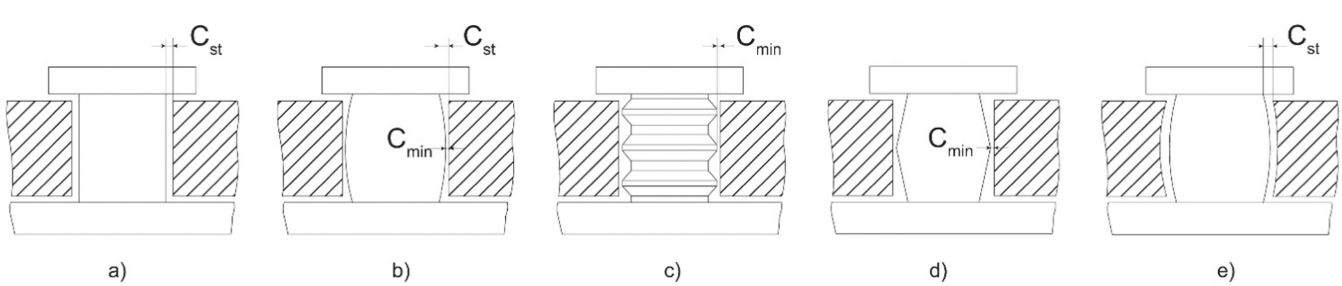

Fig. 4. Different proposed shapes for a pin-joint in order to minimize the clearance in the mechanism; a) a standard pin joint shape with standard clearance (C_{st}); b) a drum-shaped pin-joint in which the minimum clearance (C_{min}) is smaller than the standard clearance; c) a worm-shaped pin-joint; d) a drum-shaped pin-joint with a sharp transition; e) a drum-shaped pin-joint with a constant clearance.
Adapted from [17,30,37–39,43].

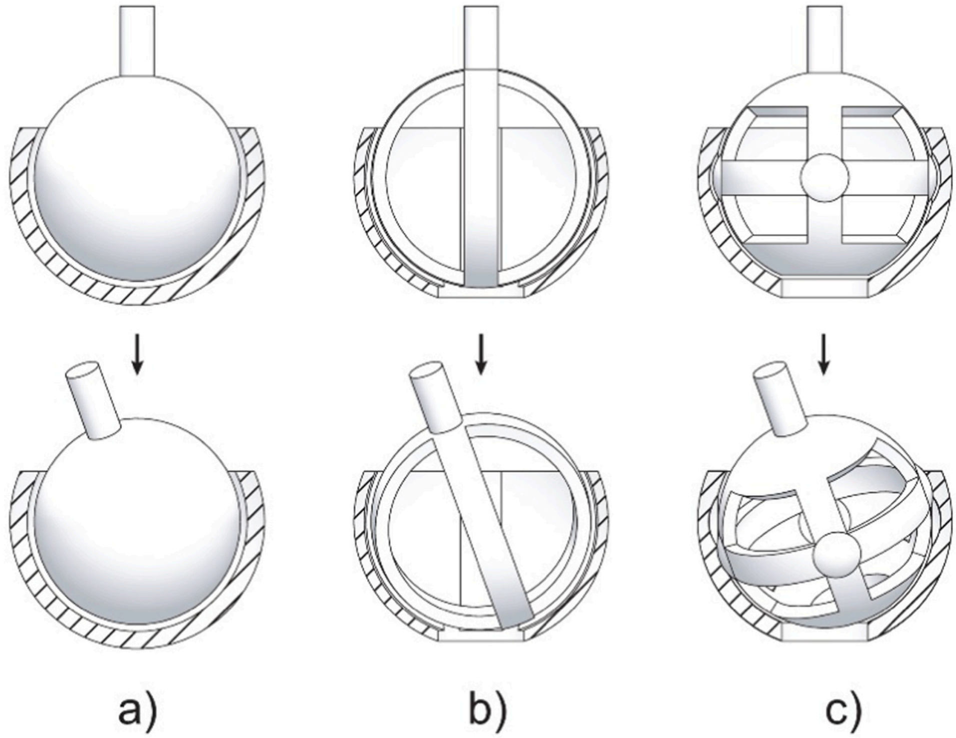

Fig. 5. Examples of non-assembly ball joints.
A) a regular ball joint; b) design of a ball joint with open structure and ridges in order for it to be posable, adapted from [31]; c) design of a ball joint with open structure and marker-dents in order for it to be posable, adapted from [36].

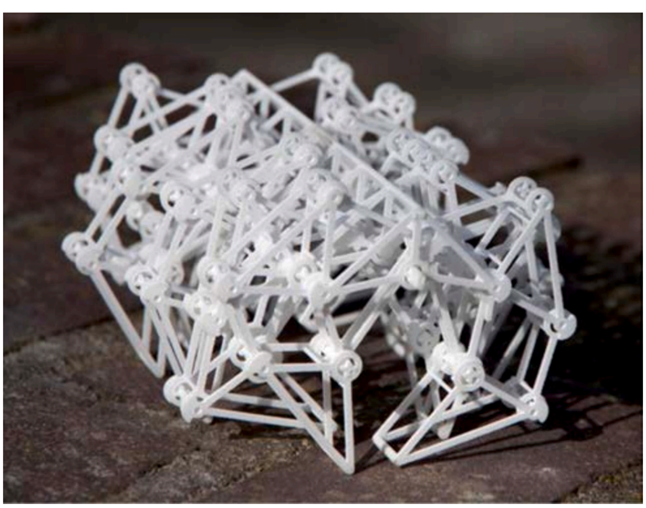

Fig. 6. A non-assembly 'Strandbeest', a mechanical walking robot, by Jansen et al. [16].

Table 2
Challenges and design solutions for mono-body mechanisms, with corresponding references proposing/applying the solution.

Problem	Design solution	Reference
limited mobility	increase flexure length	[45–48]
parasitic motion	avoid elastomeric materials	[49]
	mirror the geometry/apply symmetry	[50–52]
	design geometric restrictions	[45,53]
	replace serial mechanisms with parallel mechanisms	[45,51]
	increase structural stiffness of connecting structure	[46]
support structures	decrease overhang angle	[46,54, 55]
	scale part down	[53]
	choose appropriate build direction	[55]
poor fatigue life	provide a uniform stress distribution	[53]
	avoid motion in the plastic region of the material	[51]
	choose appropriate build direction	[51,53]
limited material options	adjust geometry according to material properties and choose suitable joints	[47,48, 50]

4.2. Mono-body

4.2.1. Design challenges

Challenges related to the design of mono-body mechanisms are summarized in Table 2.

Mono-body mechanisms often suffer from limited mobility, due to rigidness of the material. By increasing the length of the flexural part of a hinge, it is possible to create a large displacement joint. Spirals and helices are an ideal shape for this, since they can have long flexural members, while maintaining a compact size. Scarcia et al. [45] optimized the design of a spiral torsion spring to obtain a deflection/bending angle of up to 90°, as illustrated in Fig. 7a. Mirth [47] proposed a tri-spiral hinge, shown in Fig. 7b, which is self-centering due to its structure. The design of the hinge allows multiple links to be stacked on top of one another with a connecting core, creating 2D-layered mechanisms that can be printed without support on an FDM printer. Different bending angles can be obtained by means of adjusting the core diameter, spiral angle, pitch and thickness. Bending angles of up to 180° were developed this way, although the authors noted that the joints limited to 90° were most stable.

A major disadvantage of increasing the range of motion of flexural joints is parasitic motion, which is out-of-plane, unwanted motion. To combat this, Tavakoli et al. [49] suggest avoiding elastomeric materials in favor of more rigid materials, since it is easier to control their bending direction. Mirth [50], Zhang et al. [52] and Tan et al. [51] have shown that by applying symmetry or by mirroring the geometry, parasitic

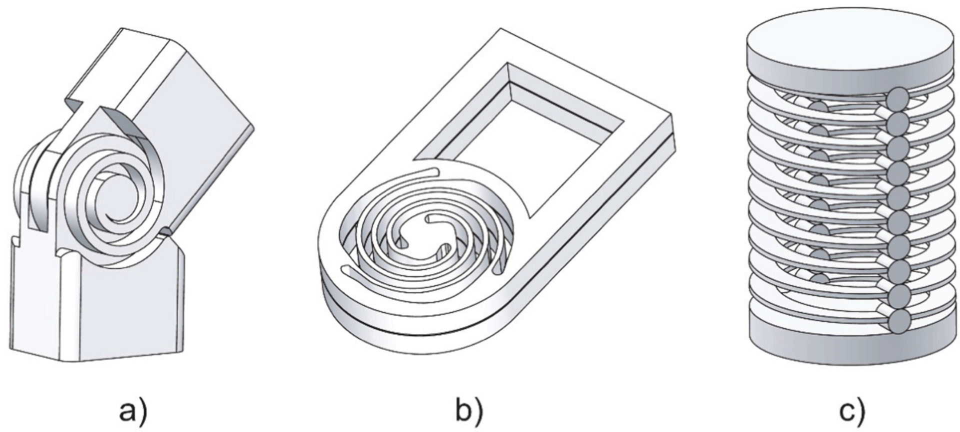

Fig. 7. Examples of mono-body hinges. a) Spiral torsion spring, based on [45]; b) tri-spiral hinge, based on [47]; c) helical joint with rolling contacts, based on [53].

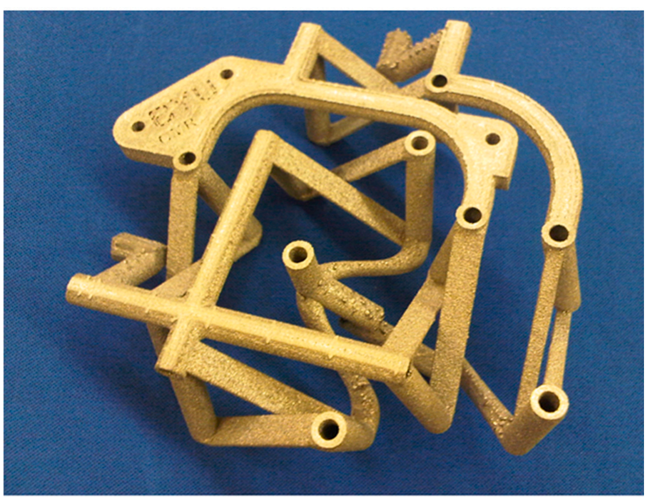

Fig. 8. Design of a pointer mechanism for space applications by Merriam et al. [46].

motion can be reduced. Geometrical restrictions can be built into the design of a joint in order to ensure its stability [45,53]. Hu et al. [53] developed a flexible joint for snake-like instruments. A helical structure is used to obtain the mobility needed for a bending motion, while rolling contacts are added in the helix to prevent undesirable compression (Fig. 7c). Merriam et al. [46] designed a pointer mechanism for use in space applications (Fig. 8). In order to maintain a suitable range of motion, a thin, long flexure was used for the joints. For their application it was important that the mechanism had high precision and reliability. To achieve this, they made the structure surrounding the flexures as rigid as possible, which has been found to significantly improve the precision by reducing parasitic motion [46,56].

The need for supports is less of a problem for mono-body mechanisms than it is for multi-body mechanisms. However, supports can still be undesirable. Decreasing the overhang angle is the most effective way to reduce the need for supports [46,54,55]. For mechanisms that are sufficiently small, support material may not be necessary. An example is the flexible helix joint designed by Hu et al. [53]. They found that due to the small size of the helix, the helix could be printed without support, with only a small deformation. This deformation was small enough not to affect the functioning of the joint.

The fatigue life of flexural parts is directly influenced by the positioning on the build plate [51,53]. Ideally, all flexure parts should be located in planes parallel to the build plate, in order to ensure that the stress of bending will be carried by the material itself instead of by the inter-layer adhesion [51]. This will provide the optimal strength to the mechanism, even if this would mean that more support material is necessary. Additionally, for the longest life cycle, motion in the plastic region of the material should be avoided [48,51]. Bai and Rojas [57] tested two versions of a compliant joint based on a cross-four-bar-linkage for a prosthetic finger. In order to mimic human joints, they added a contact surface in one instance and gear teeth in the other. A finite element analysis showed that the maximum stresses in the teeth-guided joint were 55% less than in the contact-aided joint, meaning that the gear teeth aided in distributing forces from the flexible compliant links.

Although the materials options for AM are increasing rapidly, there are still limited options to choose from. For mechanisms with flexural parts, it is important that the used material has a certain flexibility and is not too brittle [50]. The best way to create joints and flexural elements is to adjust the geometry according to the material properties [47,48,50]. Mirth [47,50] has shown that longer beam-type flexural elements can successfully be used for more brittle materials.

4.2.2. *Design opportunities*

Mono-body mechanisms are generally more difficult to produce with traditional manufacturing techniques than with AM [58]. However, they have many advantages, such as frictionless motion [45,46,51,58], fewer parts [58], and affordability [45,51,59]. Since there are no clearances for mono-body mechanisms, it is possible to generate a smooth displacement and an accurate, predictable range of motion [51,60]. Especially in the medical domain, this can be a great advantage. Zanaty et al. [61] designed a multi-stable device that can be used to puncture the retinal vein in the eye. Since this vein is extremely small, it is nearly impossible for a surgeon to accurately puncture inside the vein. The mono-body mechanism of Zanaty et al. [61] can be pre-programmed to specific puncture distances, eliminating the need for any force or displacement from the surgeon. Krieger et al. [62] showed that their monolithic robotic gripper could follow a predefined path. The structure they designed consists of solid segments, connected by thin flexure hinges. By changing the geometry of the contact surfaces between the solid segments from flat to an interlocking structure, a predefined end pose could be enclosed within the geometric design of the gripper.

Another advantage of mono-body mechanisms is the possibility of creating small sized or scalable mechanisms, which can be created without taking clearances into account [45,59]. Salem et al. [59] designed a microbiota sampling capsule, which needed to be small enough to be able to travel through the entire gastrointestinal tract. The capsule contains a small sponge, which, once in contact with liquids, swells and activates a bi-stable 3D-printed mechanism. The bi-stable mechanism closes the capsule, safely sealing in a microbiota sample.

Table 3
Challenges and design solutions for material-based mechanisms, with corresponding references proposing/applying the solution.

Challenge	Design solution	Reference
Limited mobility	Position hinge in the middle of the joint instead of at the edge	[63]
	Adjust hinge geometry	[63,64]
	Use functionally graded materials	[65]
Low rigidity/stiffness	Use multiple layers	[66,67]
Parasitic motion	Add elastomeric constraints	[68]
	Use appropriate cross-section	[69]
	Shorten length of hinge	[69]
Spring behavior	Add a negative stiffness counterbalance	[70]
Poor inter-material adhesion	Add a material gradient	[66]

5. Material-based mechanisms

For material-based mechanisms, a flexible material is used for the required mobility. The flexible material can be used for the entire mechanism, or in combination with other, often rigid, materials. The challenges associated with the use of flexible materials are summarized in Table 3.

5.1. Mono-material

5.1.1. Design challenges

Hinges for the design of monolithically fabricated prosthetic fingers have been extensively researched with regards to their range of motion [63,64,71]. These non-symmetrical notch-type hinges allow for a bending motion with one degree of freedom, mimicking the motion of a real finger, as shown in Fig. 9. Liu et al. [64] compared nine different geometric shapes for the flexure hinges, which they 3D printed and tested for bending performance (Fig. 9a-j). Mutlu et al. [71] compared three different geometrical shapes by experimental testing of 3D printed models and by FEM analysis (Fig. 9a, c, f). Although Liu et al. [64] and Mutlu et al. [71] used the same 3D printing process and a similar material, their results differ. According to Mutlu et al. [71], an elliptical hinge shape showed the best bending angle, while Liu et al. [64] concluded that rectangular-shaped notches had the best bending angle. The difference in result may be due to the testing method: Liu et al. [64] used a tendon-driven testing set-up where a weight was connected to the tendon wire at a perpendicular angle, while Mutlu et al. [71] applied a force directly to one end of the hinge at an angle smaller than 90 degrees. Zhou et al. [63] considered only one flexure hinge geometry, but instead of placing the flexure hinge towards the edge of the joint, they positioned it towards the middle of the joint, as shown in Fig. 9j. While still maintaining a non-symmetrical bending motion, they reported that it provided a greater bending displacement, as well as a reduced chance of buckling.

The hinge designs shown in Fig. 9 have only one degree of freedom. When it is necessary to have two degrees of freedom, the flexural part of the joint needs to be slender in two directions, creating a fragile part in the joint and increasing the chance of parasitic motion. Zhou et al. [63] solved this for their opposable thumb design by using two consecutively placed one degree of freedom joints with slightly different bending axes to create the required range of motion. In order to combat the parasitic motion in their surgical end-effector, Johnson et al. [69] designed the flexible hinges with a cross-section that only allows deflection in a single plane. In their case this was a rectangular cross-section. In addition, by limiting the length of the flexible members they were able to reduce parasitic motion.

Low rigidity is one of the side-effects of using a flexible material. Liu et al. [72] used this to their advantage for a compliant finger designed to grasp fragile objects, since they found the finger could deform easily around objects, creating an increased contact region. Zhu et al. [66] designed a pneumatically driven robotic finger, in which they used the principle of layer jamming, in which multiple layers are pressed onto one another to create the required stiffness. Similarly, Mutlu et al. [67] integrated an extra wall into their pneumatic soft gripper to adjust the stiffness.

5.1.2. Design opportunities

The advantage of mono-material mechanisms compared to mono-body mechanisms, is their ability to achieve a greater range of motion in less space with a simpler geometry [69,73]. As a result, they can be produced in smaller size ranges [74]. Flexible materials have also proven to be useful for pneumatically actuated grippers, since soft materials are able to conform to the contours of an object [75]. AM makes it possible to design pneumatic actuators with a controlled bending motion by means of local changes in geometry. For mono-material mechanisms, this can be achieved by alternating straight sides, with sides with a bellows-like structure that is able to expand [75–77]. Mutlu et al. [67] created two pneumatic 'fingers' actuated by one central bellow that can exhibit bending motion. In these fingers an extra wall was added, perpendicular to the bending direction, which increased the bending stiffness and the gripping force of the gripper. Blanes et al. [48] presented a number of different pneumatic actuators utilizing air chambers and rotational links to obtain controlled motion for food grippers (Fig. 10). They were successful in creating helical, spiral-shaped and bellows-shaped air chambers, which combined with rotational links created linear, rotational, and mixed motion.

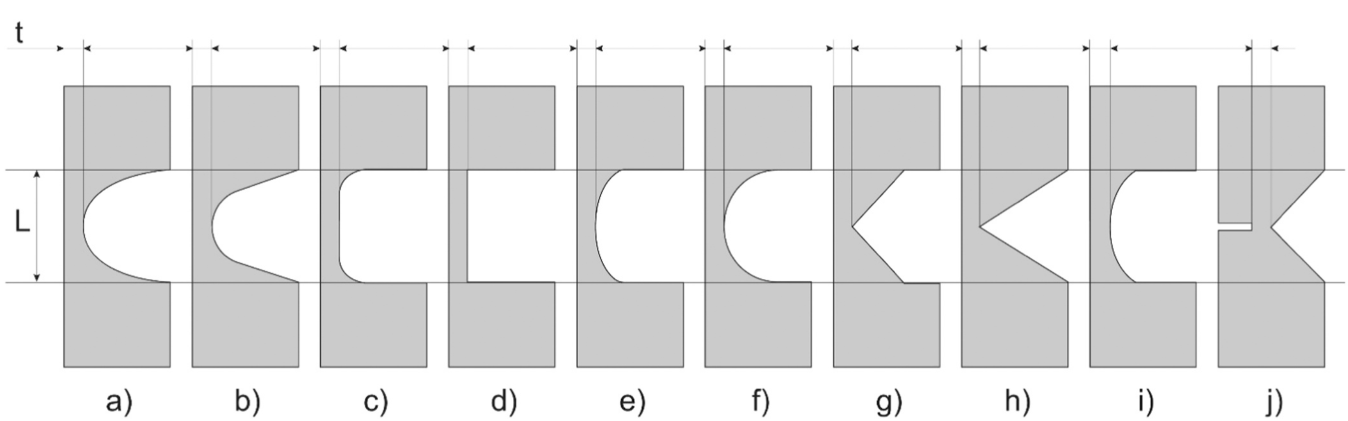

Fig. 9. Side view of flexible hinges used in prosthetic fingers, with equal hinge thickness (t) and hinge length (L), the only difference is in hinge geometry. Adapted from Liu et al. [64] (a-i), Mutlu et al. [71] (a, c,f) and Zhou et al. [63] (j).

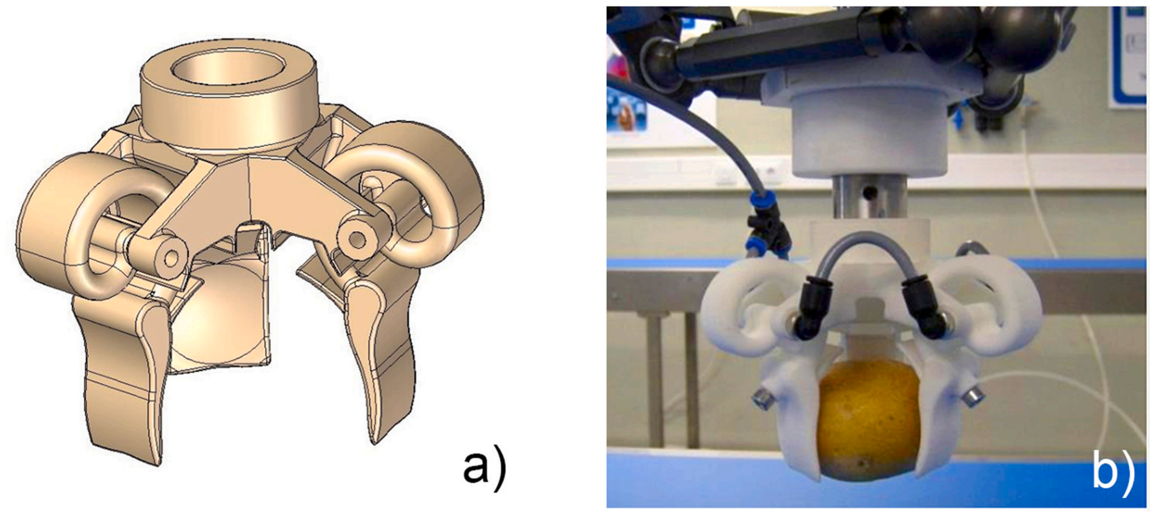

Fig. 10. An example of a mono-material pneumatic gripper, utilizing a spiral-shaped air chamber and rotational links. a) CAD-model of the pneumatic gripper; b) the 3D printed prototype [48].

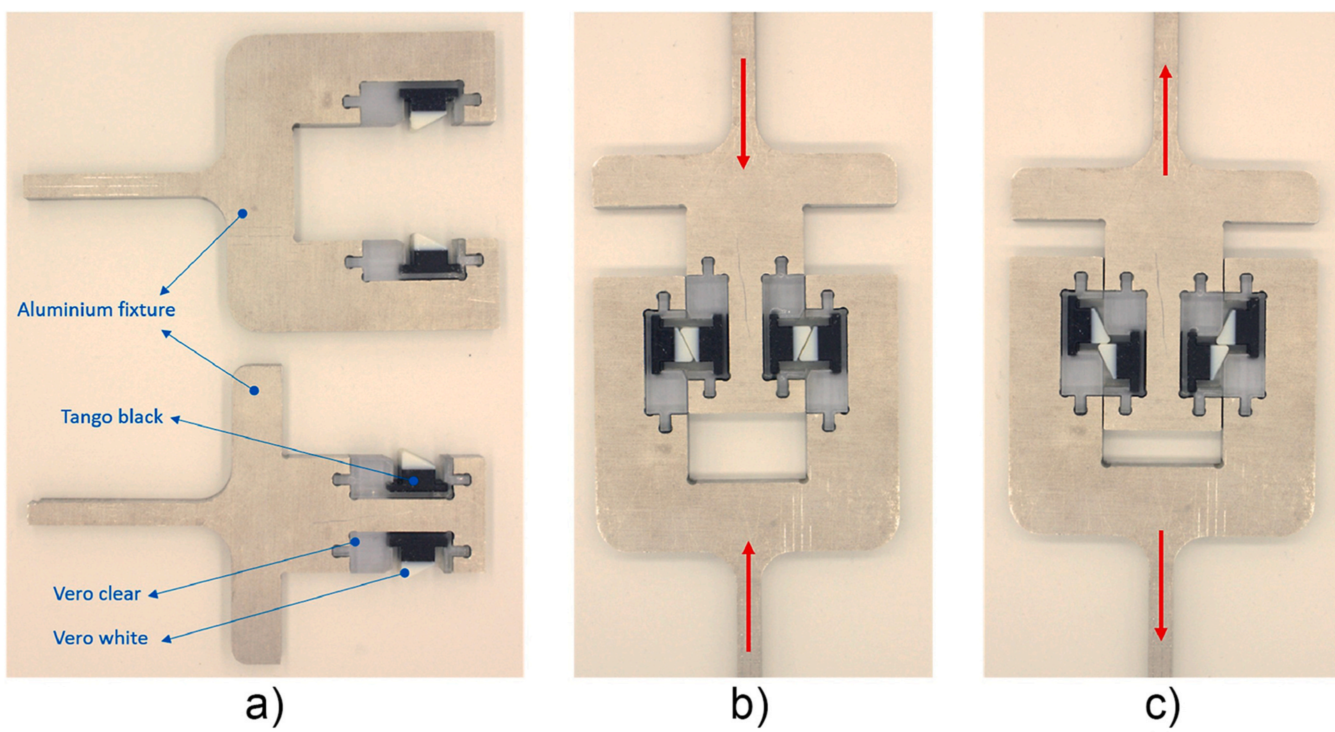

Fig. 11. Multi-material ratchet mechanism by Sakhaei et al. [73]. a) The testing set-up for the mechanism with an aluminum fixture; b) initial set-up; c) locking direction.

5.2. *Multi-material*

5.2.1. *Design challenges*

The options for multi-material printing are limited to the available printers that can print multiple materials, and the available materials themselves. The most utilized combination of materials is the combination of two polymers, a rigid and a flexible one [68–70,73,78,79]. A combination of metals has also been used [65], as well as a flexible polymer combined with a magnetic-particle polymer composite [80].

It seems intuitive that the area of a multi-material structure that is most likely to fail is the border between the flexible and rigid material. However, Sakhaei et al. [73] found that for their ratchet-like mechanism this was not the case (Fig. 11). Instead, failure occurred in the area with highest concentration of stress in the flexible material. They hypothesized that this is due to the fact that both materials were acrylate-based, resulting in a strong chemical bond between the materials since they have a similar base. To facilitate proper border adhesion when a chemical bond is not possible, a material gradient can be used between the transition of the materials [69].

One of the properties of all material-based mechanisms is that the hinges will show spring-like behavior due to the elastic properties of the material. This can be an advantage, depending on the application, however, in applications where multiple stable positions are required, this might pose a challenge. In order to combat this, Bruyas et al. [70] designed a statically balanced compliant joint. They combined a mirrored helical structure made of a rigid material, with a core made of an elastic material. In order to create static balance, they added two spring-like elements to the sides, which exhibit bi-stable behavior. This way, they managed to create two stable positions for the joint.

The flexibility of the material can also be a challenge for the functionality of the mechanism. Castledine et al. [81] used multi-material AM to design a flexible segment for a robotic gripper, in which the flexible material was used for the core of the gripper, with rigid disks dispersed along it for guidance of the actuation tendons. However, the core proved to be too flexible to accurately steer the segment. Therefore, in order to create sufficient torsional rigidity, interlocking segments were added to the rigid disks.

5.2.2. Design opportunities

In all examples of multi-material mechanisms, the elastomeric material is used for the joints in the mechanism, while the rigid material provides the structural integrity. The advantage of using an elastomeric material for the joints in multi-material mechanisms is the same as for mono-material mechanisms, with the advantage that the addition of a rigid material makes it easier to increase the required rigidity for other parts of the mechanism. In addition, multi-material AM makes it possible to create functionally graded structures, in which two or more materials are mixed in different ratios to create varying material properties. This was applied by Jovanova et al. [65] to create compliant metal hinges with different bending angles.

Mirth [78] used a sheet metal design approach to create a multi-material mechanism. The mechanism can be printed entirely flat on the print bed, after which it is folded into its functional shape, much like the production of sheet metal parts. The design consists of a layer of flexible material that forms the base for the hinges, onto which a rigid material is printed for the structural parts. The advantage of this approach is that it significantly reduces the printing time and no support material is required.

Multi-material AM has also been used to create pneumatic and hydraulic mechanisms. The addition of a rigid material has certain advantages over only using a flexible material. MacCurdy et al. [82] adjusted a multi-material Polyjet 3D printer to print non-assembly hydraulic walking robots. To make the robot completely non-assembly, they also printed the hydraulic fluid inside the bellows by using a cleaning fluid provided by the printer manufacturer (Fig. 12). A mix of materials with varying stiffness was used to create bellows that were flexible enough, but were also able to resist the fluid pressure. Similarly, Skylar-Scott et al. [83] created a pneumatically actuated walking robot by developing a new AM method for multi-material printing in which they could define per voxel which material to use. The walking robot uses both a flexible and rigid material for the air chambers. The flexible material allows the legs to ‘bend’, and because of the rigid material the robot is able to carry a weight of up to eight times its mass.

6. Pattern-based mechanisms

Pattern-based mechanisms use a relatively simple mechanism as a basic building block, or cell, which is patterned or repeated to obtain a complex transformation. This can be useful to create modular mechanisms that can easily be adapted to different applications or tasks, since they use the same basic mechanism as building block.

Ion et al. [84,85] designed mechanisms inspired by metamaterials that allow for controlled directional movement. Their mechanisms consist of rectangular cells, which can either be rigid, connected by a living hinge, or be able to make a shearing motion. The cells were arranged in rectangular arrays. Alternating shearing, hinged and rigid arrays resulted in mechanisms such as a door hinge (Fig. 13b), pliers, and a switch. Ou et al. [86] also used rectangular cells as a basic building block, which they described as four-bar linkages. Placing hinges in different locations on the four sides of the rectangular cell, resulted in scaling, shearing, twisting and bending motions of the single cell, illustrated in Fig. 13a. By combining and patterning different cell configurations, they were able to create displays with encoded messages, foldable boxes for packaging (Fig. 13a) and a foldable helmet. Mark et al. [88] used 3D metamaterials with auxetic behavior to design a robot that can climb up and down in a tube. The robot contains one bellow actuator, which is connected to two metamaterial structures: the first behaves like an auxetic material with negative Poisson’s ratio, and the other with a similar positive Poisson’s ratio. Because of the contraction of the bellow actuator, the materials are either pushed or stretched; alternatingly taking on the role of anchor or walker. This way the robot is able to crawl up the tube. The two metamaterials were designed in such a way that they have an exact inverse Poisson’s ratio. The structure did need supports, therefore the cells needed to be large enough for removal of the support material.

Liu et al. [89] and Zhao et al. [87] took inspiration from origami for their pattern-based mechanisms. Liu et al. [89] adapted a classic origami design, a twisted tower consisting of modular segments, for 3D printing. In the adapted design, the entire structure can be 3D printed as a pre-folded mechanism using multi-material AM, where the flexible material functions as the folds in the paper. The tower can be actuated by cables, and is able to generate linear, bending and twisting motions, making it suitable to function as a robotic arm. Zhao et al. [87] used an origami cube as a basic cell, with flexure hinges located along the edges of the cube. Variations in the configuration and structure of the cubes resulted in different transformations, as shown in Fig. 13c.

The advantage of pattern-based mechanisms is that it is relatively easy to design the simple mechanism that can be used as the basic cell

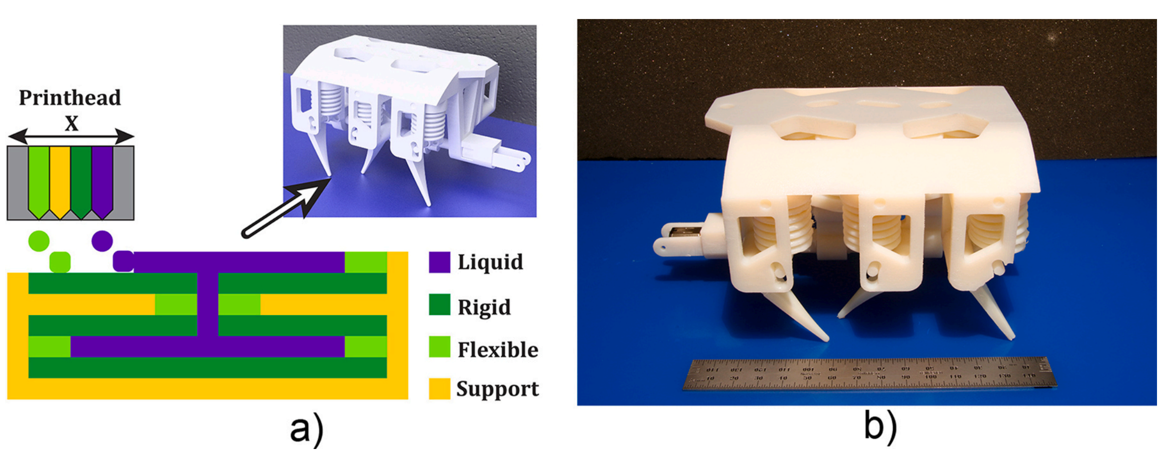

Fig. 12. Non-assembly 3D printed hydraulic walking robot by MacCurdy et al. [82], a) showing the different materials and order in which the bellows where printed; b) the final prototype.

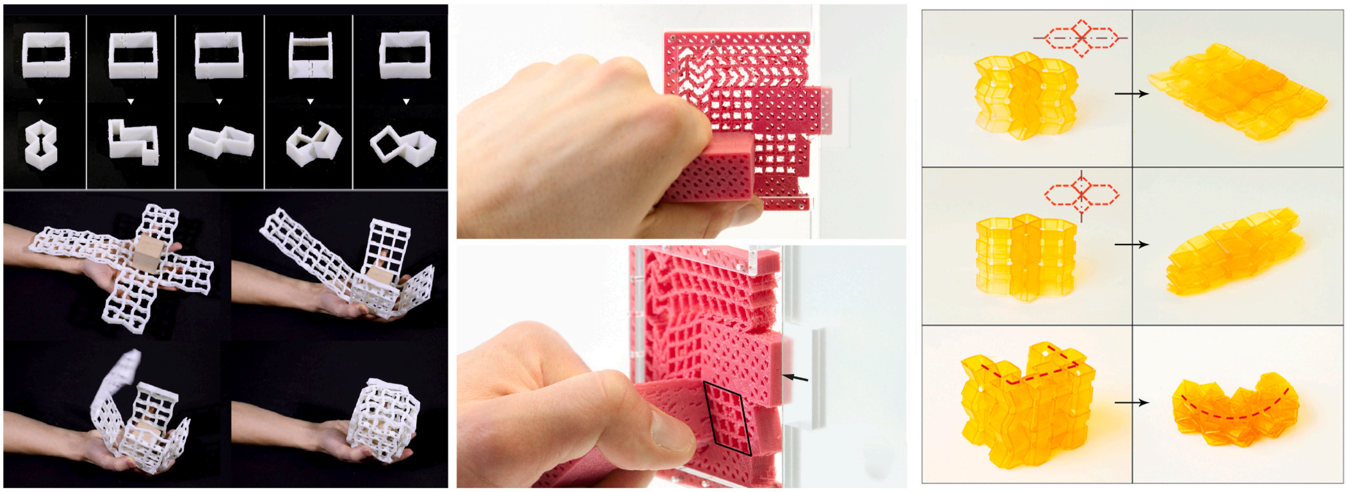

Fig. 13. Examples of pattern-based mechanisms. a) Five different transforming configurations for a single cell (top), cells applied in a folding box design (bottom) [86]; b) pattern-based door latch mechanism [84]; c) different origami-based folding structures, the unfolded structure on the left, folded on the right [87].

[90]. For FEM calculations, analyzing one segment requires less computational power than analyzing the entire structure [91]. They can also be adapted easily for different applications. In addition, the basic cell can function as a test-segment to optimize the production settings for 3D printing [92]. However, the real difficulty lies in designing the pattern within the mechanism. Simple functions can be designed by hand, but for more complex mechanisms this becomes a difficult task. Therefore, software programs and models that can generate the pattern based on an input and desired output are particularly useful for pattern-based mechanisms [84–86,90,93].

7. Self-assembly

In addition to mechanisms that do not need to be assembled after production, AM has given rise to mechanisms that can assemble themselves after printing. Self-assembling behavior can for instance be obtained by making use of shape-memory materials [94–96]. These materials have the capacity of holding a temporary shape, but will return back to their original shape when subjected to an external stimulus, such as heat [94]. This allows the mechanism to both assemble and disassemble itself. Another approach is making use of the shrinking behavior of PLA to create self-assembling mechanisms [97,98]. 3D printed PLA shows shrinking behavior along the printing path direction [93], therefore by varying the printing direction within a part it is possible to use the shrinking behavior to design pre-programmed bending. Bending can be triggered by heating the material. A number of interesting mechanisms have been created using this approach, such as compliant forcipes [93], chair legs that can lock themselves in place after assembling [93], self-tightening knots [94], and soft grippers inspired by natural tendrils [98]. The advantage of these examples of self-assembling mechanisms is that the starting configuration of the mechanism is often a simple structure that can easily be 3D printed without support structures, whereas the final assembled state would be more complex and difficult to print. In addition, assembly can be triggered whenever it is required [99].

8. Discussion

8.1. Design solutions for non-assembly mechanisms

The use of AM technologies for the production of mechanisms is still experimental. Therefore, it is always necessary to thoroughly know the specifications of the chosen printing process in order to design a well-working mechanism [34]. Knowing the minimum resolution, overhang angle, minimum wall thickness and material properties is important for the printability of the design. The reviewed literature shows that there are a lot of best practice examples of non-assembly mechanisms, from which design solutions can be extrapolated to be implemented in future designs.

The design of joints is an important part of non-assembly mechanisms [16,17,29,30,32,33,35,37,39,43]. Often a single joint is designed, printed, and tested for its kinematic performance. When the joint is functioning satisfactorily, it is applied in the complete mechanism. However, there are a few downsides to this approach. First, build direction is an important consideration for the functioning of the joint. If the integrated mechanism contains joints at different construction angles, it might mean that the build direction is not the same as for the tested joint, and thus its performance might be affected. Second, integration of the joint into the mechanism may lead to unexpected surprises. For example, Jansen et al. [16] found that the single pin joint they had designed and tested as part of their 3D printed 'Strandbeest' worked with minimal clearances. However, when the entire integrated mechanism was 3D printed, it turned out to be impossible to remove all the support material from the joints, because they were blocked by other parts of the mechanism. As a result, the joints needed to be redesigned with larger clearances for cleaning. It is, therefore, important to consider the design of the mechanism as a whole.

With the developments in material suitable for AM, a large number of flexible and elastic materials have become available. These materials have been quickly adopted for the design of joints for typical 'soft' applications, such as prosthetic fingers [63,64,71] and soft robotics [66,67,80]. The advantage of a flexible material is that the joint geometry can be less complex and more robust, as compared to mechanisms using only a rigid material. This leads to the possibility of scaling mechanisms down to a smaller size while still being 3D printable. The option to combine multiple materials in a single production step opens the door to a new range of possibilities, such as creating functional gradients between materials. This can be used for instance to control the bending behavior of joints [65], to reinforce transitions between materials, or to create fully functional advanced assemblies, such as the hydraulic robot of MacCurdy et al. [82], in which even the hydraulic fluid was printed. Multi-material AM also shows great potential for creating innovative bio-inspired designs, since in nature a combination between flexible and rigid materials is common.

Metal AM shows great potential for use in both rigid parts and flexures in non-assembly mechanisms. However, only a handful of the examples in this review make use of metal AM [17,37,38,46,53,56,65,100]. This may be because compared to conventional technologies, metal AM processes such as Powder Bed Fusion or Selective Laser Melting have a few distinct disadvantages. First, they leave the part with a relatively rough surface quality, which increases friction and wear on parts with surface-to-surface contact. This is especially problematic for multi-body mechanisms, since the wear on parts during use increases the clearances and can make the mechanism unstable [17]. Since non-assembly mechanisms also cannot be disassembled, most surface finishing processes will not be able to reach the internal surfaces of joints. Second, the resolution of AM metal processes is still quite poor. This makes it difficult to create tight clearances, or flexures that are thin enough to serve as a joint. With advances in AM it is expected that these disadvantages will decrease, although more research into design methods specifically for metal AM will be valuable for a wide adoption of metal AM mechanisms.

Pattern-based mechanisms make optimum use of the shape complexity offered by AM. Their design shows a lot of similarities to the design of metamaterials; structure and material are closely integrated. Further development of the pattern-based design approach could lead to a fusion between designed mechanisms and metamaterials. Technological advances in AM processes in terms of resolution and multi-material options offer many possibilities to create these types of mechanisms on a smaller scale with ever-increasing functionality.

One of the ways to deal with the immense design freedom offered by AM is using computational models and software to aid in the generation of functional mechanisms. As the design of mechanisms becomes more complex, and more components of an assembly are integrated, the more value these tools can add to the design process. Software editors, design tools, and libraries with a standardized selection of functions are being developed to make it easier to design and produce 3D printable mechanisms [84,101,102].

An effective, conventional solution to actuate any mechanism is by using cables to transfer movement from one part of the mechanism to the other. For non-assembly mechanisms, this means the mechanism itself is 3D printed, after which the tendons are manually inserted [49,53,58,63,64,69,71]. This can be a quite laborious process, depending on the complexity of the mechanism. Possibilities of integrating strings into 3D printed parts that have been researched include the use of an embroidery machine as an extra production step [103], or by embedded 3D printing, in which the fibers are added during printing either manually [104] or by adding a fiber extrusion head to an existing 3D printer [105]. Additional research into this area is needed in order to eliminate the final assembly step for tendon-actuated mechanisms.

Self-assembly can be seen as the next step in the development of non-assembly mechanisms, since they can avoid some of the disadvantages associated with non-assembly. For instance, with self-assembly it is possible to print the casing of a mechanism as a flat structure with the required functional components pre-assembled on top, which folds exactly into place after printing, creating an enclosed mechanism without the disadvantages of needing a support structure. This could pave the way for structures that are simple to produce with AM and, after printing, self-assemble into a complex mechanism. In addition, being able to control the exact time when the mechanism assembles and, more importantly, disassembles, could be an enormous advantage, for instance for medical applications.

8.2. Advantages and disadvantages of non-assembly mechanisms

Non-assembly mechanisms provide many advantages, the most obvious being a reduction in manufacturing steps for complex products [28], leading to reduced costs. Non-assembly mechanisms lend themselves to being scaled down to sizes where assembly of separate parts is a difficult and tedious process. In addition, complex mechanisms can be produced without considering adjustments for assembly. This can improve reliability and safety, because of an elimination of additional assembly steps [14]. Non-assembly mechanisms have the potential to function instantly after fabrication, which is beneficial for plug-and-play solutions for urgent needs, or in remote locations [14]. Non-assembly also reduces the need for specialized assembly and fine tuning knowledge, reducing the need for training in production facilities and making production more accessible for laypeople [14].

However, there are also a number of disadvantages of non-assembly. In traditional mechanism design, the material choice and production process can be optimized for each part, since they are all produced separately. For non-assembly mechanisms, all parts are made with the same process and often the same material. Since most multi-material 3D printers are not yet capable of using more than two similar materials at the same time, such as two plastics or two metals, compromises in material and geometry have to be made. Even though no assembly after production is necessary, this does not always mean the mechanism is ready to use out of the printer. Usually, one or more post-processing steps, such as removing support material or polishing surfaces, are necessary. Especially removing supports can be a time-consuming process [89].

Since the design of these mechanisms is non-assembly, it also means that they cannot be disassembled. Therefore, replacing or servicing parts is difficult or impossible. Due to the current limited quality of 3D printed parts, this would suggest that currently non-assembly mechanisms are mostly applicable to non-critical products, disposable products or products with a short life span. A possible solution for products that need to be serviceable is printing them partially disassembled, or designing them in such a way that they can be (partly) taken apart when necessary [16].

When the disadvantages of the non-assembly approach cannot be ignored for a design, it is always possible to combine this approach with parts that do need to be assembled. This should be a consideration based on the functional concerns, such as the kinematic and strength requirements of a joint, and manufacturing concerns, such as the required

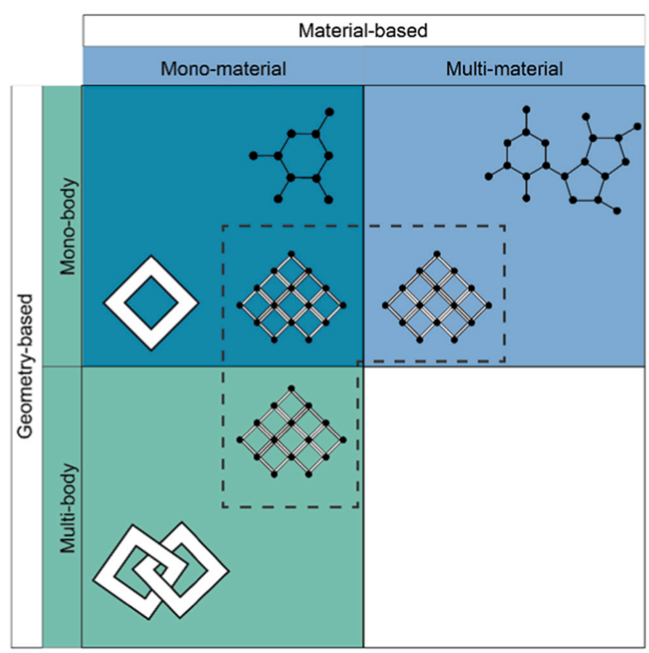

Fig. 14. This figure shows the combined design space for geometry-based and material-based mechanisms. All examples discussed in this review fall within the blue and green fields. The icons represent the categories as presented in Fig. 1. The fourth field, of multi-body multi-material mechanisms, remains empty, since no examples were found that fall within this category. This indicates a promising direction for future research. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

clearances and need for support material [33].

8.3. Future directions

As can be seen from the examples provided in this review, AM of non-assembly mechanisms is still in its infancy. We can distinguish a trend within our proposed categorization, from more traditional mechanism designs that consist of multiple bodies, to innovative designs that show an unprecedented integration between material, geometry and structure, embracing all opportunities that 3D printing brings.

An interesting perspective can be offered when combining the design opportunities as presented in this review for the category of geometry-based mechanisms and material-based mechanisms, as has been done in Fig. 14. If we consider that each of the fields in this figure signifies the design space for the given categories, then the examples selected in this review all fall within the blue- and green-colored fields. The figure indicates that the design space for mono-body and mono-material mechanisms is overlapping, which is caused by the fact that there are many variations of flexibility when considering material properties. Depending on the properties of the material, the appropriate design solutions should be chosen.

Pattern-based mechanisms are a special case. Since the building block that they use is in essence a simple mechanism, when zooming in to this level, it can be seen that it is possible to classify the single cell as a geometry-based or a material-based mechanism. An example of a geometry-based cell is given in Fig. 13a, where rigid-body hinges are used in the cell, and an example of material-based cells is given in Fig. 13b, where a flexible material is used for the hinge. Therefore, the same design solutions can be applied as for geometry- and material-based mechanisms on a cell level, however for the overall mechanism overarching design solutions are necessary.

The fourth field in Fig. 14 remains empty, since no examples of mechanisms have been found that combine the design opportunities of multi-body mechanisms with those of multi-material mechanisms. This shows a potential direction for future research. We imagine that inspiration for these kinds of mechanisms can be found in nature. For instance, joints in the human body can be described as multi-body multi-material joints: two rigid, separate bones, for which the movement is controlled or restricted by flexible tendons.

9. Conclusion

The advances in AM technologies have led to novel ways of creating fully-functional mechanisms that can be created in a single production step. These come with their own challenges for design and production. This review has provided a state-of-the-art of non-assembly mechanisms, in which special attention has been paid to the production challenges inherent to AM and the design solutions used to overcome these. Although each AM process has its own specific limitations and guidelines, from the examples found in literature it can be seen that for certain groups of mechanisms similar problems are encountered regardless of the technology, for which it is possible to use similar design solutions. Therefore, the found examples were categorized according to the type of mechanism to which similar design solutions can be applied. The examples in this review show that it is possible to create a wide range of mechanisms using AM, ranging from the traditional type of multi-body mechanism, to increasingly popular compliant mechanisms and futuristic mechanisms that are able to assemble themselves. The simplified production of non-assembly mechanisms makes them advantageous to use in many applications, such as healthcare and aerospace engineering. In order to continue the development and implementation of non-assembly mechanisms, it is important to pay attention to tools and methodologies that help designers and engineers navigate the immense design space offered by AM.

Funding

This project has received funding from the Interreg 2 Seas Programme 2014-2020 co-funded by the European Regional Development Fund under subsidy contract No. 2S04-014.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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