IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 13 February 2024, accepted 21 February 2024, date of publication 23 February 2024, date of current version 1 March 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3369493

TOPICAL REVIEW

Manufacturing of 3D Printed Soft Grippers: A Review

KAI BLANCO, EDUARDO NAVAS, LUIS EMMI, AND ROEMI FERNÁNDEZ
Centre for Automation and Robotics (CAR), CSIC-UPM, 28500 Madrid, Spain

Corresponding authors: Kai Blanco (kai.blanco@csic.es) and Roemi Fernández (roemi.fernandez@car.upm-csic.es)

This work was supported in part by MCIN/AEI/10.13039/501100011033 under Grant PID2020-116270RB-I00; in part by MCIN/AEI/10.13039/501100011033 through the European Union NextGenerationEU/Plan de Recuperación, Transformación y Resiliencia (PRTR) under Grant PDC2021-121578-I00 and Grant TED2021-132710B-I00; and in part by Spanish National Research Council (CSIC), Proyecto Intramural Inteligencia Artificial y Mecatrónica Cognitiva para la Manipulación Robótica Bimanual—2º Fase (IAMC-ROBI-II), under Grant 202350E072.

ABSTRACT Soft robotics technology has been rapidly expanding in recent years due to its advantages in flexibility and safety for human operators. Within this trend, soft grippers enable more delicate and adaptable manipulations, minimizing damage to the final object or the environment. 3D printing has recently emerged as a new manufacturing method for robotics, offering novel materials and design possibilities. The use of soft materials, such as thermoplastic elastomers (TPE) or silicone based elastomers, in 3D printing has enabled soft grippers to demonstrate their potential, leading to new applications in the medical, industrial or even the agricultural field, as well as improved performance. The ongoing synergy between soft robotics and 3D printing holds promise for continued breakthroughs, expanding the horizons of possibilities in these dynamic and evolving technological domains. This article provides a comprehensive review of the latest adavancements related to 3D printed soft grippers, as well as a discussion of the challenges ahead for this emerging field; in terms of limited resources, manufacturing costs and design process; emphasizing its growing importance in the fields of robotics and automation.

INDEX TERMS 3D printing, additive manufacturing, robotic manipulation, gripper, soft robot.

I. INTRODUCTION

3D printing, also known as additive manufacturing (AM), is an additive technique defined as the method of creating objects from 3D model data by joining materials together in a layer-by-layer fashion, contrary to subtractive manufacturing techniques like conventional machining [1]. This manufacturing methodology offers the possibility of working with complex geometries that would be extremely difficult to produce through any other method. It also enables the creation of mechanisms and structures in a one-shot configuration. Thus, 3D printing offers significant flexibility in potential designs, enabling novel developments and fresh perspectives for designers, and facilitating the creation of new technologies and applications.

In recent decades, 3D printing has gained popularity across various industrial sectors. Initially, it was predominantly used as a rapid prototyping method. However, its utilization in the final part manufacturing process has seen a substantial increase. One of the industries that has widely embraced 3D printing as a manufacturing technology is robotics. From utilizing polymers like Polylactic acid (PLA) and Acrylonitrile Butadiene Styrene (ABS), to employing alloys like AlF357 (aluminium alloy), the robotics field has seamlessly integrated 3D printing into every stage of the creation process, resulting in more efficient and robust components.

One robotic component that has embraced this new technology and witnessed significant performance benefits is the so-called gripper. A gripper refers to a robotic end-effector designed to grasp and manipulate objects against external disturbances [2]. Conventionally, robotic grippers are composed of rigid elements that are combined using movable links. These links are connected with actuators to generate movement. While this approach has proven sufficient for many applications, the challenges increase when more complex movements and functionalities are

The associate editor coordinating the review of this manuscript and approving it for publication was Yangmin Li.

required [3], [4]. To deal with these problems, soft materials have been added as part of the design, allowing for new functionalities while simplifying the overall gripper's composition. Thus, soft robotics employ soft materials which, through the use of various types of actuation, whether pneumatic, tendon-driven, or SMA, generate motion. Soft robotics offer several advantages over traditional robotics. These flexible materials allow for compliant designs, enabling the reproduction of complex behaviors with the use of just one component and fewer actuators, enabling robots to adapt to unstructured environments, maintaining efficiency in task performance. Additionally, soft robots can work alongside humans without posing any risk to them. Typically, these parts are usually manufactured by the molding of two-component silicone such as Polydimethylsiloxane (PDMS), EcoFlex or DragonSkin. However, the main disadvantages of these manufacturing processes are the elevated cost of the materials used as well as the design limitations imposed by the molds' capabilities. Fairly recent developments in AM technologies have allowed the use of soft materials as building element. Here, 3D printing offers a more robust design solution, allowing not only the creation of intricate designs but also their optimization and simplification. Modern design methodologies, such as topology optimization, enable the production of more efficient components. These maintain or even enhance their functionality while reducing manufacturing time and costs [5].

Soft robotics development to date using AM technologies demonstrate the inherent benefits in this type of design. What's more, the production of soft actuators and grippers using 3D printing as the main manufacturing technology has had a sustained interest over recent years, as is shown by Fig. 1. This is mostly due to the reduction of manufacturing time and cost when compared with traditional methods, as well as the possibility of creating more complex designs. These advancements, which may enable a new generation of robots, are still mostly carried out independently. There is a need to register and analyze these new approaches, showcasing the main AM technologies used as well as the employed manufacturing materials. Also, a categorization of the main design structures is needed, as well as the most used actuation methods. The challenges faced by this evolving technologies are also of great importance. For this, 36 articles chosen from Google Scholar and Scopus are analyzed in this review. To be selected, they had to meet a series of requirements: (i) contain the keywords *gripper* and *3D printing*, (ii) the 3D printers used must utilize some kind of soft material, (iii) the soft material must be used to manufacture the gripper itself or most of it and in case of individual soft actuators being researched, (iv) there must be at least one reference or example of its possible application as a gripper. The chosen articles were then revised and their content categorized for an in detail analysis.

Although there exists similar literature to this review, it generally does not go into detail when presenting key topics related to 3D printing in the manufacturing of soft grippers. These reviews present in the literature often lack a proper categorization of the different polymers used, as well as the various manufacturing methods applied through AM [6]. Knowing the advantages and limitations of different polymers and AM methods can help improve the design process. Another significant difference in this review, compared to the already existing literature, is the analysis of 3D printing as a direct end when manufacturing soft grippers with the use of soft materials. That is, this review only takes into account those articles in which the soft gripper is manufactured directly by using AM and soft materials, as stated above. On the contrary, the trend in other types of articles is the analysis of 3D printing as a means to that end; i.e., the use of additive manufacturing is allowed in the creation of molds and other non-compliant components, with the final manufacturing of the soft gripper being carried out with elements such as Polydimethylsiloxane (PDMS) and casting methods [7], [8], [9]. Another key factor to consider is the relative novelty of this specific use for 3D printing. The reviewed articles range, as seen in Fig. 1, from 2016 up to 2023, with the vast majority (24 of 36 articles articles) published from 2019 onwards. This review is therefore, up to date, one of the most recent works in this field, analyzing the latest research presented and updating existing work.

Therefore, a critical review of 3D printed soft grippers is presented, covering the different technologies, physical principles and design fundamentals applied.

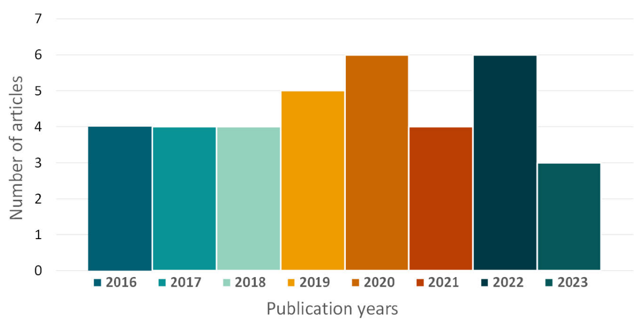


FIGURE 1. 3D printed grippers articles published by year.

II. ADDITIVE MANUFACTURING PROCESSES

This sections analyzes the techniques based on additive manufacturing used in the reviewed articles, showing the main working principles of each of them. By exploring these 3D printing methods, we aim to provide insight into the cutting-edge techniques that have enabled many researchers to push the boundaries of creativity and efficiency.

Table 1 shows a summary of the results of the analysis that was carried out to determine which technologies were used as well as their impact on the review. Taking these results into account, this section will focus mainly on Fused Deposition Modeling (FDM) and PolyJet technology, since they are the most used in the reviewed literature, although some of the main characteristics of the rest of the technologies will also be reviewed.

TABLE 1. Analysis on the different additive manufacturing technologies used.

Technology	Bibliography	Reference
FDM	23	[10]–[32]
PolyJet	8	[33]–[40]
SLA	1	[41]
SLS	1	[42]
μCLIP	1	[43]
DLS	1	[44]
PμSL	1	[45]

A. MATERIAL EXTRUSION

This AM technology relies on the extrusion of the main building material, in gel form, through a nozzle. Once extruded and deposited onto a printing bed, it solidifies, due to a change in temperature or a chemical reaction. It is widely used due to its simplicity in operation and relatively low cost. There are two main material extrusion technologies employed in the reviewed articles: Fused Deposition Modeling (FDM) and Direct Ink Writing (DIW).

1) FUSED DEPOSITION MODELING (FDM)

Fused deposition modeling, also referred to as Fused Filament Fabrication (FFF), can be defined as the process of creating objects by fusing together successive layers of material [46]. Unlike traditional subtractive methods that involve cutting material away from a block to create an object, FDM is an additive process: it works by adding material to manufacture an object. This technique operates on the principle of extruding thermoplastic polymer through a heated nozzle, which then deposits the material onto a build platform. As each layer is added and subsequently cooled, the object gradually takes shape. FDM is widely employed in various industrial sectors, ranging from rapid prototyping and product development to creating functional end-use parts, tooling, and even artistic creations. The layer-by-layer approach allows for intricate designs and complex geometries, and the choice of thermoplastic materials offers a wide array of properties, enabling the production of parts with varying characteristics such as strength and flexibility. These materials typically consist of a thermoplastic matrix with additives or fillers to introduce new features or enhance performance.

FDM printers can be categorized according to various criteria. One of them is the format in which the material is presented for its use. 3D printers require the thermoplastic to be fed into the machine, and this thermoplastic material typically comes in two formats: filament spools or pellets.

- **Filament:** Filament is commonly used for harder polymers. The thermoplastic is made into filament, usually 1,75mm or 3mm in diameter, and is winded in spools for better use and handling. Once loaded into the machine, it's pushed into the extruder body. There, it's heated to the required temperature using an electrical resistance and then extruded through the nozzle onto the build plate. An overview of this type of printers can be seen in Fig. 2a. These printers are the most prevalent, ranging from basic models found in hobby shops to industrial-grade printers capable of using engineering polymers like Ultem® (polyetherimide). They are also capable, if the printer's design allows it, of combining multiple filaments in one print in order to produce multi-material objects with some new wanted properties.
  Within filament printers, there is a subgroup that depends on the location of the drive gear with respect to the extruder head. These can be classified as direct drive or bowden. The first one is mostly used for soft filaments or when maximum precision is required. The drive gear responsible for the filament feeding is located as close to the heating block as possible, ensuring minimum travel distance between the two. On the other hand, in bowden systems, the drive gear is located far from the extruder head. These two are usually connected with a PTFE tube for the filament to go through. This is usually done in order to reduce weight in the X axis of the printer, producing better print quality, with more precise movements. However, its use is not recommended with flexible filaments, as the force needed in the extrusion tends to deform the filament and block the PTFE tube.
  Liu et al. [19] designed, via topology optimization, a constant-force compliant finger. For its manufacturing, commercial flexible filament Filastic was used, as well as a Prusa i-3 FDM filament printer. This design was then used in the manufacture of a three-fingered constant-force compliant gripper that allowed manipulation of fragile objects. This shows the advantage of FDM technology over traditional manufacturing methods, as it enables rapid production of test models, as well as easy adaptation to new design methodologies. This model was designed considering both the output force and the output displacement, for the topology optimization.
- **Pellet:** Normally used when the desired object size and material preclude the use of filament spools or when the thermoplastic is too soft or too brittle to be made into filament. The working principle is similar to any other FDM machine, but with the addition of a feeder screw. This screw is responsible of pushing the pellets into the heated part of the extruder and through the nozzle [17]. This type of printers are also use in materials research, as it enables the possibility of combining various materials or additives directly in the printer.
  For example, Georgopoulou and Clemens [17]used a pellet based FDM system to produce soft compliant robotics grippers with integrated sensing elements. The main advantage of using pellet-based FDM technology is its ability to operate with low Shore hardness materials, as is the case in this article, where styrene-based thermoplastic elastomers (TPS) with a Shore hardness of 25A were used. Filament-based FDM printers are typically limited to a Shore hardness greater than 60A. The use of pellet technology also enabled the use of a

custom mixture of a conductive thermoplastic composite to produce the extruded piezoresistive material.

2) DIRECT INK WRITING (DIW)

The DIW technique involves a printing method wherein material is extruded through a pressurized nozzle. It employs a computer-controlled robot to navigate the dispenser filled with printed ink, constructing geometries layer by layer [47] It is similar to traditional FDM printing, with the main difference being that in DIW the material is usually in gel from. It is also usually preferred when working at the meso- and microscale [48], [49]. It differs from other AM technologies in that it is not limited by the class of material, as long as it maintains its properties, such as viscoelastic properties, during extrusion [50].

Zolfagharian et al. [14] applied this technology in the manufacturing of a bi-stable soft robotic gripper. Silicone-ethanol and silicone elastomer were used for the fabrication of the gripper. For each layer, Part A and Part B of each component were injected into a silicone static mixer, which proceeded to print with the resulting extruded material. Once deposited onto the building platform, the curing process starts, allowing the addition of a new layer. This method facilitates the integration of time-dependent reconfiguration, enabling the creation of the thermally responsive gripper. Furthermore, it supports the utilization of custom-made inks, printing devices with intricate structures, superior mechanical characteristics, and improved functionalities [51].

B. MATERIAL JETTING

This method generates intricate and finely detailed components by jetting and solidifying layers of liquid photopolymer. Within this technology, there exist PolyJet. It's particularly known for its capacity to craft parts with remarkably refined surfaces and tight tolerances, up to 0,1-0,3mm [52]. Another key characteristic is the extensive array of material available, even allowing translucent properties. The production process of an object is structured as follows:

- **Material Jetting:** liquid photopolymer materials are jetted onto the build platform in ultra-thin layers, similar to how an inkjet printer deposits droplets of ink onto paper.
- **Multi-Material usage:** One of the key strengths of PolyJet technology is its ability to simultaneously jet different materials, allowing for the creation of parts with varying properties in a single print. This makes it ideal for producing realistic prototypes, multi-material assemblies, and visually appealing models. In addition to the model material, a removable support material is often jetted simultaneously. This support material helps to maintain complex geometries, overhangs, and delicate features during printing. After the print is complete, the support material can be easily removed by hand or with water or other dissolving agents.
- **UV Curing:** As each layer of resin is deposited, it is immediately exposed to ultra violet (UV) light. This UV light rapidly cures the material, transforming it into a solid state. The process ensures that each layer is well defined and will retain its shape.
- **Layer-by-Layer Build:** The layer-by-layer build process continues, with the print head depositing the material and the UV light curing it, until the entire part is completed. The layer resolution in PolyJet printing is exceptionally fine, allowing for intricate details and smooth surfaces.
- **Post-Processing:** Once the print is finished, the completed part is typically removed from the build platform. Depending on the application, further post-processing steps such as cleaning, curing under additional UV light, or smoothing the surface might be performed to achieve the desired final result.

PolyJet 3D printing finds extensive application across industries like product design, healthcare, consumer goods, and automotive. Its importance lies in the capability to produce intricate prototypes and models composed of multiple materials. The technology achieves a combination of precision, surface excellence, and material flexibility. As a result, it becomes an invaluable asset for a diverse range of applications that demands both elevated precision and aesthetic finesse [53].

In this matter, Howard, David et al. [33] used PolyJet technology to produce a one-shot 3D printed multimaterial soft robotic jamming gripper. The use of this technology enabled the manufacture of this gripper, composed of different materials with varying Shore hardness. This is achieved through its layer-by-layer fabrication process, as well as its ability to extrude multiple materials at once. These characteristics differentiate this AM technology not only from traditional manufacturing methods, but also from other AM processes.

C. VAT PHOTO-POLYMERIZATION

These AM technologies work in a similar way as PolyJet does. The basic working principle remains the same in all of these: a photo-curable resin is used as the main building material which is then cured by UV light. The exact resin type, the source of the UV light and other key characteristics change with each technology:

- **SLA:** also known as stereolithography, SLA is a widely used resin-based additive manufacturing (AM) technology for part production. The process involves a vat containing liquid resin, typically with a clear membrane at the bottom. Utilizing an UV laser, SLA cures the resin layer by layer, similar to the FDM (Fused Deposition Modeling) process. These layers are built on to a moving platform, so that when each one is properly cured, it is forced away from the membrane, leaving new uncured resin below.

  Yang, Yang, et al. produced a Fin Ray inspired soft robotic gripper with force feedback. It was manufactured in a single piece on a ZRapid Tech model iSLA 660 light-curing 3D printer using Formlabs elastic resin material. The use of SLA technology enabled the fabrication of the complete 3D model, making it easy and cost-effective to produce. Compared to traditional manufacturing techniques, the proposed method allows the creation of large 3D soft models in a single volume.

- **DLS:** stands for Digital Light Synthesis, also known as CLIP (Continuous Liquid Interface Production^{TM}). DLS is a photochemical procedure that transforms liquid plastic resin into solid components. The process involves directing ultraviolet light via an oxygen-permeable window into a reservoir containing UV-curable resin. By projecting a series of UV images, the resin gradually solidifies and the build platform rises. The core of the DLS process lies in a crucial element known as the dead zone. This zone, created by the oxygen-permeable window, represents a narrow liquid interface of uncured resin positioned between the window and the printing part. Illuminated by light, this dead zone allows the resin located above it to undergo curing, forming a solid component. This process avoids the curing of the part onto the window itself. As the printing progresses, the resin flows beneath the curing part, ensuring a continuous liquid interface and a layer free object.
  In this trend, Koivikko et al. [44] proposed the use of DLS technology to produce the flexible body of a 3D printed pneumatically controlled soft suction cup for the gripping of fragile, small and rough objects. Using DLS over any other AM technology ensured a faster manufacturing process as well as more homogeneous properties.
- **μCLIP:** Micro Continuous Liquid Interface Production is a technology that evolves from the original CLIP, driven by the need for high-resolution microscale manufacturing. One benefit of μCLIP over conventional CLIP technology lies in its capacity to craft detailed microstructures with fine precision. This attribute makes it highly compatible with scenarios encompassing microfluidics, microelectronics, and analogous domains that demand intricate components. Additionally, the continuous liquid interface enables the seamless production of smooth prints, avoiding the downsides of peeling or layering, challenges commonly encountered in conventional resin-based 3D printing techniques.
  Shao et al. [43] produced a 3D printed magnetically-actuating micro-gripper capable of operating in air and water using this technology. It enabled them to 3D print this model in a single piece, on a microscale. The use of this technology was also key to achieving the particular type of actuation proposed, as it is capable of working with custom-made photopolymerizable resins; in this case, the resin used was created by the mixing CN982A75 and PEGDA with Irgacure 819 and Fe_3O_4 nanoparticles, making it magnetically responsive.
- **PμSL:** Projection Micro Stereolithography represents an advanced additive manufacturing technique that creates intricate three-dimensional items with exceptional precision and detail. In the process of PμSL, a liquid photopolymer resin is subjected to a controlled arrangement of ultraviolet light utilizing a digital light projector or a similar light source. As a result of this exposure, the resin progressively solidifies layer by layer, culminating in the creation of a fully realized object. The strengths of PμSL become evident when addressing the need for intricate detail, fine features, and a flawlessly polished surface texture. PμSL permits the manufacturing of intricate, small-scale components characterized by remarkable accuracy and resolution.
  An example of this is presented by Ge et al. [45], with the use of SMP (Shape Memory Polymers) in the manufacturing of temperature driven soft grippers.

D. POWDER BED FUSION

Unlike the AM technologies presented in the previous subsections, these utilize a fine powder as the main building material that, by some alteration, combines into a solid object. This powder may not always be polymeric, as some metal alloys could be used.

Among the most widely used powder-based techniques, Selective Laser Sintering stands out. SLS creates three-dimensional objects through the targeted fusion of powdered materials, commonly polymers or metals, layer by layer, facilitated by a potent laser. The procedure starts by applying a fine layer of the powdered substance onto a build platform, followed by meticulously melting particles in the desired configuration as dictated by the cross-section of the 3D model. With each layer undergoing sintering, a fresh powder layer is added. An exceptional facet of SLS is the lack of support structures, as the adjacent powder serves as support for the piece itself. Upon full sintering, excess powder is removed, revealing the final printed object. The SLS technology is esteemed for its adaptability across a spectrum of materials, empowering the production of prototypes, functional end-use parts, and even intricate designs that might pose challenges for alternative manufacturing techniques.

Leveraging this technology, Sun et al. [42] created a lightweight robotic gripper featuring 3D topology-optimized adaptive fingers. The use of SLS technology made it possible to manufacture complex 3D models without the need for support structures, facilitating the post-processing stage.

III. SOFT MATERIALS

Soft materials are those that undergo some observable deformation in response to external stimuli, also known as hyperelastic behaviour [54]. This is one of the primary challenges encountered when 3D printing with flexible materials, as even the slightest deformation could render the final object unusable.

This section evaluates the 3D printed soft materials employed in the reviewed articles. Only the materials that were specifically mentioned in each article have been taken into account, as many of them do not offer any details

TABLE 2. Comparison between the different additive manufacturing technologies.

	Material extrusion	Material jetting	Vat photo-polymerization	Powder bed fusion
Multimaterial	Yes (depending on the printer)	Yes	Ongoing research	No
Support	Usually needed (there exists soluble supports)	Usually needed	Yes. Easy to remove	Depends on the technology
Pros	• Able to operate with engineering materials • Wide range of thermoplastics • Custom-made materials	• Fast printing process • Able to mix different materials • Wide range of materials • Smooth surface finish	• Good surface finish • Relative isotropic properties • Capable of working at the micro-scale	• Able to print parts with good mechanical properties • Relative low cost • Able to print one-shot models
Cons	• Slow manufacturing process • Anisotropic properties • Poor surface finish	• Relatively weak models • Expensive materials and synthesis process • Loss of mechanical properties over time	• Single material printing (commercially) • Material contraction during printing • Low mechanical properties	• Rough surface finish • High porosity • Hazardous material

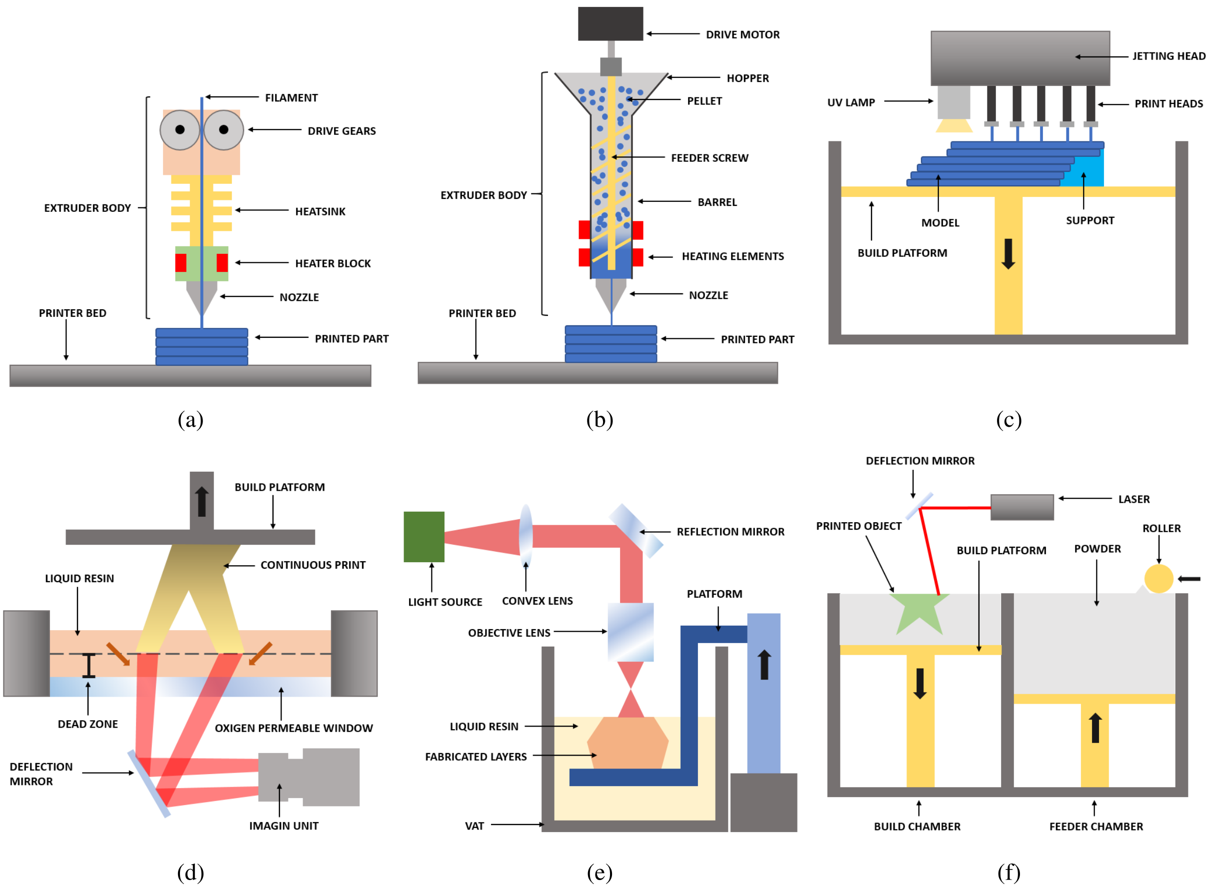


FIGURE 2. Additive manufacturing processes (a) Filament extruder overview, (b) Pellet extruder overview, (c) PolyJet, (d) Digital Light Synthesis (DLS), (e) Projection Micro Stereolithography (PμSL), (f) Selective Laser Sintering (SLS).

about what material was used in the manufacturing of the soft gripper. Due to the high use of FDM and PolyJet AM technologies in soft gripper manufacturing, as seen in Fig. 1, most of the catalogued materials belong to these two technologies. All soft materials are categorized according to the format in which they are presented for their use. Then, each type is analyzed, offering some technical information, as well as an overview of the manufacturing process and challenges.

A. THERMOPLASTIC ELASTOMERS (TPE)

It is mainly used in FDM technology. TPEs have been commercially available for much longer, but are relatively new to the 3D printing sector. TPEs are less expensive,

TABLE 3. Soft materials classification.

Class	Curing	Type	Materials	Bibliography	References
Thermoplastic elastomers			TPE	9	[12], [16]–[19], [21], [24], [25], [29]
Thermoplastic elastomers			TPU	10	[10], [11], [15], [20], [22], [23], [26], [28], [30], [32]
Thermoplastic elastomers			TPS	1	[17]
Thermoset elastomers	Photo-curable	Resins		3	[41], [43], [45]
Thermoset elastomers	Photo-curable	Commercial formulations	Agilus	4	[33], [34], [39], [40]
Thermoset elastomers	Photo-curable	Commercial formulations	Vero	6	[33], [34], [36], [37], [39], [40]
Thermoset elastomers	Photo-curable	Commercial formulations	Tango	3	[34], [36], [37]
Thermoset elastomers	Photo-curable	Commercial formulations	DM-RGD	2	[35], [39]
Thermoset elastomers	Photo-curable	SMP		2	[31], [45]
Thermoset elastomers	Self-curing		Silicone elastomers	1	[14]
Others				1	[42]

have greater availability, and are better for lighter, more flexible products [55]. They usually come in two formats: filament and pellet. Regarding soft materials, the filament format is mostly used for higher shores, while the pellet format is used for ultra-soft materials. Pellet printers are also used if any other material or additive is added while printing, as well as for higher material usage. Within TPEs there are specific materials that are also used in AM, such as Thermoplastic Polyurethanes (TPUs) and Styrene-based Thermoplastics (TPS), as seen in Table 3.

- **TPU:** Thermoplastic Polyurethane. It is known for its exceptional flexibility, resilience, and resistance to abrasion, making it optimal for producing objects that require both strength and elasticity. TPU's ability to retain its properties across a wide range of temperatures, combined with its ease of 3D printing, has made it a popular choice for creating functional prototypes, durable parts, and products in diverse fields, such as automotive, healthcare, and consumer goods. TPU's properties can be modified by adding additives and fillers, enabling the wide range of products already available in the market of 3D printing supplies.
- **TPS:** Styrene-based thermoplastic elastomers are versatile polymers that combine the flexibility and resilience of rubber with the processability of thermoplastics. TPS allows for the creation of flexible parts, providing a unique balance between strength and flexibility. Its use in not as extended as TPE or TPU, with fewer examples and applications in the robotics field.

Despite the rapid growth in the use of flexible materials in AM, successful prints require the printer's capability to operate with these materials, as well as adjustments to settings such as print speed, temperature, and bed adhesion methods. Careful attention to these factors enables the production of intricate and functional objects with a wide range of applications.

B. THERMOSET ELASTOMERS (TSE)

It is typically used in liquid or gel form. When these materials are used, each layer is precisely deposited onto a build platform. The main characteristic of this kind of AM technology is the rapid curing mechanism, typically involving UV light or other curing sources. This quick solidification enables the creation of intricate and detailed objects with extraordinary precision. It is a preferred choice in industries where high-resolution and finely detailed parts are essential. There are two main subgroups, depending on the source of the polymerization process:

- **Photo-curable:** This type of TSE polymerizes through the application of UV light, allowing the combination of monomers into polymer chains.
  - Resins: Used in technologies such as μCLIP [43] and PμSL [41]. These can be modified by the addition of other elements such as magnetic particles, fillers, which gives the final part new or enhanced properties.
  - Commercial formulations: Used in specific AM technologies, such as PolyJet. The following are specific formulations or combination of other resins created to achieve particular properties, as seen in the articles reviewed:
    - Agilus: It is a resilient resin characterized by its exceptional tear resistance and elongation at break properties. It is used for creating concept models and rubber-based components such as handles, seals, anti-slip surfaces, and any parts that will undergo repetitive flexing and bending.
    - Vero: Combines fine detail visualization with resilience. Allows for smooth, accurate prototypes, surgical models or moving and assembled parts.
    - Tango: Emulates soft-touch coatings, nonslip surfaces or rubber surrounds among others.
    - DM_9860, DM_9850, DM_9840, RGD_8520: Created by mixing other already existing resins, such as Vero and Tango, in order to modify the already existing properties.
  - Shape memory polymers (SMP): This type of polymers, once conformed, can alter their shape by the application of external stimuli such as electric impulses or temperature variations. This property enables them to be temporarily deformed and then recover their original shape when activated.

    Shape memory polymers are part of the emerging field known as 4D Printing. This evolving area represents a targeted advancement from traditional 3D printed structures, impacting attributes such as shape, properties, and functionality. It is capable of achieving self-assembly, multifunctionality, and self-repair [56], [57]. This technology utilizes materials such as hydrogels or shape-changing polymers, along with shape memory alloys [58], often seeking to mimic biological structures.

- **Self-curing:**
  - Silicone elastomer: Employed as a way of generating flexible components using FDM technology and two component silicone. These two components are pumped in the correct ratio all the way to a modified extruder that, after mixing these, deposits them onto the build plate for curing.

C. OTHER

When designing soft grippers, there are materials that, although they are not considered elastomers, can have similar behaviours when manufactured in specific ways. A commonly used polymer is PA2200. It is a nylon-based thermoplastic, which means it can be both flexible when thin, and rigid when thick [42]. It is also characterized by its natural strength and chemical resistance, making it ideal for many industrial applications.

These types of materials usually come in powder form and are used in technologies such as Selective Laser Sintering (SLS). Powder 3D printers use atomized materials that, through some alteration, bind together in successive layers until the final form is achieved. The specific method used for 3D printing, hardware parameters and the size of the powder particles all play a role in determining the characteristics of the finished print [59]. Depending on the final application, this piece might require further processing before use, such as dyeing or polishing. For instance, when working with nylon-based powders, the quality of their surface, once manufactured, can be improved by shot peening or polishing.

IV. SOFT DESIGN

This section encompasses the analysis of all elements related to the design and utilization of the reviewed grippers. First, an examination of the gripper geometry is performed, evaluating each commonly found fundamental element commonly found and analyzing them individually. The second part provides an overview of Finite Element Modeling (FEM) as observed in the examined articles, along with the mathematical models applied for the soft materials used. Finally, the main actuation methods used are explored and the grip tests presented for evaluation are analyzed.

A. GEOMETRY

3D printing with soft materials has led to a significant change in the design of soft gripper geometries, no longer being limited to traditional linked rigid elements or molded parts. Many modern concepts applied to soft grippers and actuators derive from the use of origami inspired designs and compliant mechanisms [60], [61], [62], [63]. These type of geometries

TABLE 4. Analyzed geometries and number of articles.

Geometry	Bibliography	References
 Finger	26	[10]–[13], [15]–[21], [24]–[29], [31], [34]–[39], [41], [42]
 Claw	8	[14], [22], [23], [30], [32], [40], [43], [45]
 Jamming	1	[33]
 Suction	1	[44]

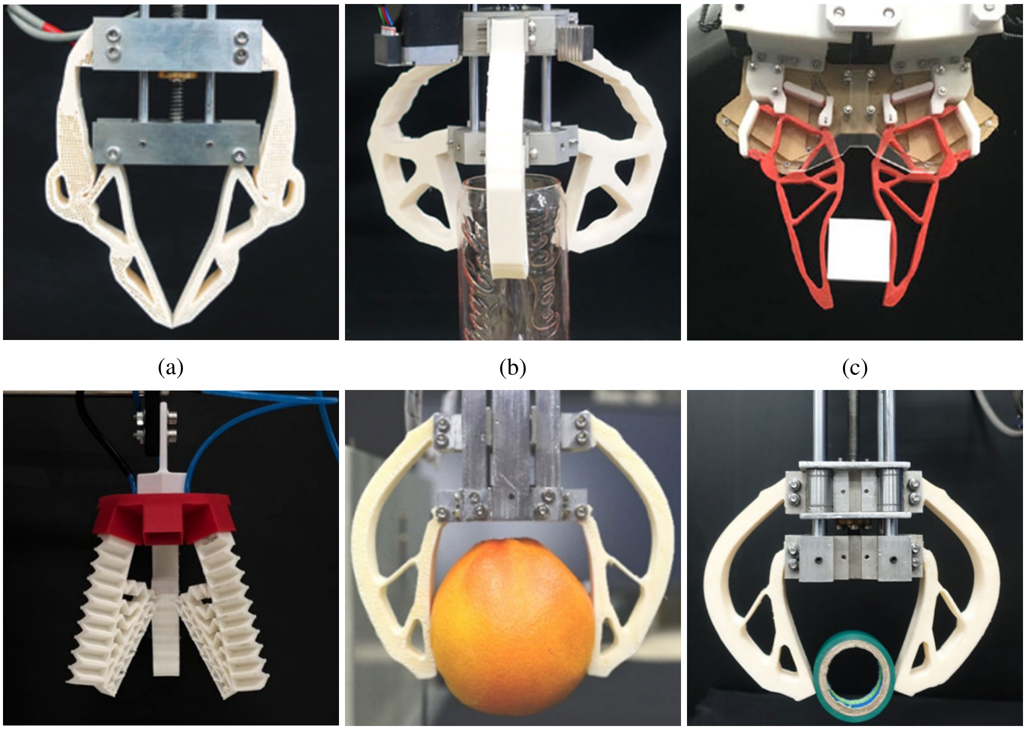
allow the grippers to be manufactured in one single piece (one-shot) and still be able to react to external stimuli and produce complex movements in response.

Although there are several types of grippers, when we refer specifically to 3D printed soft grippers, the existing options drastically narrow down to the four main types presented in Table 5. While most grippers are very different form each other, they share some common characteristics, making this categorization possible and allowing for a more comprehensive analysis. It is also important to note that the most popular type of gripper is the finger-based, as it encompasses more than 70% of the designs analyzed.

1) FINGER-BASED

Finger-like structures are the main elements of this type of grippers, and at least two of them are required to properly grasp and manipulate. The main design feature of these grippers is its modularity, since more fingers can be implemented on a rigid base if necessary. They usually have an elongated prismatic shape capable of producing movement in at least two axes through external or internal actuation (Fig. 3). They mostly benefit from compliant designs, allowing for complex movements and tilts in a single motion. Some are even equipped with internal sensors [17], [32], [36], [40] capable of registering grasping forces, angles and tensions.

In the design of these compliant fingers, usually takes part the shape optimization method known as topology optimization. An example of this method is presented by Liu et al. [19], who analyze the domain affected by the desired actuation and resulting forces to produce the topology optimized geometry of the compliant finger. This technique allows the creation of lightweight bodies capable



(a) (b) (c) (d) (e) (f)

FIGURE 3. Examples of finger based grippers. (a) Topology optimized fingers with variable infill [18], (b) Constant force compliant gripper [19], (c) Cable driven soft gripper [20], (d) 3D printed modular soft gripper for conformal grasping [28], (e) Compliant finger based gripper [24], (f) Topology optimized finger based gripper for handling fragile objects [27].

of maintaining sufficient rigidity with the minimum material used [64], [65]. It is also capable of producing grippers with variable stiffness, as well as precise and delicate movements. Due to its versatility and ease of use, it is one of the main methods used nowadays in the design of soft compliant grippers.

2) CLAW

While, in some cases, this type of gripper may be conformed by the merging of fingers, they have been categorized as such if the gripper has been manufactured in a one-shot configuration, losing the modularity that characterizes finger-based grippers. This is illustrated by Mutlu et al. [22], who manufactured a 3D printed monolithic soft gripper with adjustable stiffness using FFF technology. To be included in this categorization, the proposed gripper should also have, at least, movement in two possible axes, allowing the manipulation of various elements.

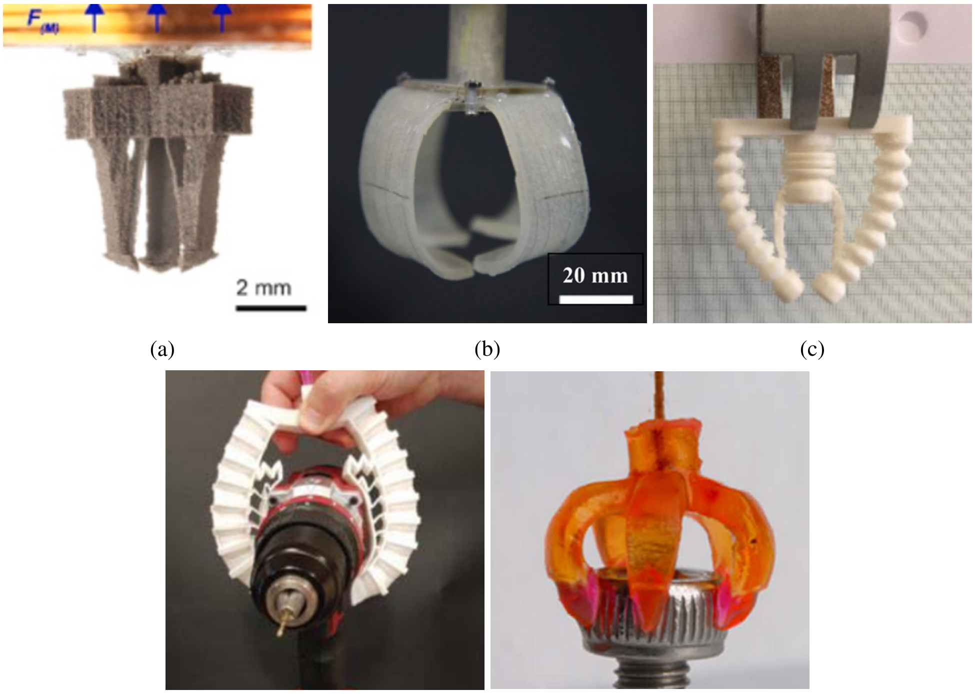
The soft and compliant nature of their fingers allows them to adapt to the shape of objects and provide a secure grip (Fig. 4). They are typically used in applications where delicate and adaptable grasping is required, such as handling soft or irregularly shaped objects [40], and they may also incorporate sensors in order to enhance their gripping capabilities and adaptability [13], [36]. Claw-based soft grippers are valued for their versatility and ability to handle objects with varying sizes and shapes while minimizing the risk of damage [22].

3) JAMMING GRIPPERS

This type of grippers uses a principle called "jamming transition" to grasp and manipulate objects. They are typically composed of a flexible membrane filled with granular materials, such as coffee grounds or small grains [66], [67], [68]. When a vacuum is created inside the membrane, the granular material becomes compacted, effectively forming a rigid structure around the object being grasped (Fig. 5).

The main key feature of jamming grippers is that they can adapt to the shape and size of the object they are trying to pick up. When air is introduced back into the membrane, the granular material loosens, allowing the gripper to conform to the object's shape. Its design is really simple, being also quite easy to manufacture and control. One limitation of jamming grippers is the difficulty in monitoring applied force, as it depends mostly on the object's characteristics [33], [66].

Concerning 3D printed jamming grippers, a good example is presented by Howard et al. [33]. In the article, they propose a novel method for manufacturing jamming grippers using PolyJet technology, in a one-shot configuration. This constitutes a great improvement over traditional jamming grippers, as this new process is not only much faster, but it also allows for complete customization of the soft gripper.



(a) (b) (c)

(d) (e)

FIGURE 4. Examples of soft claw grippers. (a) Magnetically actuated micro-gripper [43], (b) Temperature driven gripper [14], (c) Adjustable stiffness gripper [22], (d) Conformal grasping gripper [30], (e) SMP gripper [45].

FIGURE 5. 3D printed jamming gripper manufactured in a one-shot configuration using PolyJet technology [33].

4) SUCTION CUP

This type of gripper typically consist of a flexible, cup-shaped component, which is attached to a vacuum system. When this suction cup is applied to an object's surface, the vacuum system forces the cup tightly against the object, forming a secure grip (Fig. 6). This grip enables the gripper to lift, move, or manipulate the object as needed. Suction cup grippers are known for their versatility and adaptability [69], [70], capable of handling objects of various shapes, sizes, and materials, including flat and smooth surfaces or curved and textured ones.

One of their main advantages is that they are gentle on objects that demand delicate handling. For this, they are commonly used in applications requiring careful and damage-free handling, such as in industries like packaging or logistics. They are also found in clean-room environments where precision and cleanliness are the main priority [71]. The holding force can often be adjusted by regulating the level of vacuum, providing flexibility for different objects and grip strengths.

Despite their effectiveness, suction cup grippers have grasping difficulties with objects containing irregular or porous surfaces that do not create a proper seal [72]. To address this problem Koivikko et al. [44], devised a solution by creating a 3D-printed pneumatically controlled soft suction cup. This innovative gripper is designed for securely gripping fragile, small, and rough objects. The approach involves using AM technology to craft a soft body for the gripper, accompanied by an elastic film. Despite their limitations, suction cup grippers are one of the most used in industries such as aerospace and automotive.

FIGURE 6. Suction cup manufactured in flexible resin using DLS technology [44].

TABLE 5. Comparative between the different soft gripper geometries.

	Finger based gripper	Claw based gripper	Jamming gripper	Suction cup gripper
Gripping force	≤ 86.24 N [42]	≤ 4.26 N [30]	-	≤ 7.9 N [44]
Modularity	Yes	No	No	Yes
Modulus axis	≤ 3	≤ 3	≤ 3	1
Pros	• Design customization • Complex geometries • Material selection • Low price	• Lightweight • One-shot • Rapid manufacturing	• Adaptability • Soft grasping • Reduced complexity	• Gentle handling • Airtight seal • Versatility
Cons	• Material properties limitations • Layered structure • Surface finish	• Material strength • Size limitations • Post-processing requirements	• Limited load capacity • Actuation time • Complex manufacturing • Dependency on material properties	• Dependency on vacuum systems • Dependency on surface finish • Limited load capacity

B. FINITE ELEMENT MODELLING

When designing a soft gripper, it is essential to understand its behavior prior to its fabrication, in case there are any issues with its operation. Currently, a well-known and widely used method for this purpose is the so called Finite Element Modeling (FEM) [12], [13], [15], [16], [43]. FEM allows for the modeling and representation of an object's behavior when subjected to external stimuli, such as force, temperature or acceleration. To enable this calculation and representation, various mathematical models are employed according to the material's properties. In the case of the soft grippers manufactured in the reviewed articles, these are made from elastic materials, specifically hyper-elastic ones.

Hyper-elastic materials are a type of material that exhibit a highly nonlinear stress-strain behavior. Unlike linear elastic materials, such as metals and some rigid polymers, hyper-elastic materials can experience significant deformation and still return to their original shape when the force is removed. Hyper-elastic materials are mostly found in soft and flexible structures, including elastomers, rubber-like materials, and certain biological tissues. The main problem when characterizing this kind of materials is that traditional linear elastic models fail to accurately describe their behavior. There exist numerous models that aim to mathematically explain the behavior of hyper-elastic materials. Generally, they are based on the assumption that they are isotropic and nearly incompressible. However, 3D printed materials usually have anisotropic properties, as a result of the manufacturing process, which can be characterized and controlled [73], [74] to achieve specific features. This anisotropy can also be modeled numerically, as done by Khosravani et al. [75], where a finite element analysis was conducted on FDM manufactured models, utilizing the anisotropic phase-field fracture model. Another example is presented by Somireddy et al. [76]. In their article, the material stiffness of the final printed part is estimated to accurately capture its behavior. This allows the creation of a numerical model that can take into account the influence of build orientation, printing direction and layer thickness.

The most commonly used mathematical models when representing hyper-elastic materials are Neo-Hookean, Mooney-Rivlin, and Ogden. While the Mooney-Rivlin model is the primary one discussed in the reviewed articles, a brief overview of the main three models previously mentioned models will be provided, in order to offer a general understanding of their application and functionality.

- **Mooney-Rivlin model:**
  Introduced by Selvadurai, Mooney, and Rivlin [77], [78], [79]. Is an hyper-elastic material model applicable to incompressible elastic materials, where the energy density function W is a linear combination of two

invariants of the left Cauchy–Green deformation tensor B [80]. This function is defined as follows:

$$W = C_1(\bar{I}_1 - 3) + C_2(\bar{I}_2 - 3) \quad (1)$$

where C_1 and C_2 are material constants also related to the linear elastic shear modulus:

$$G = 2(C_1 + C_2) \quad (2)$$

and $\bar{I}_1$ and $\bar{I}_2$ are the first and second invariants associated with the deformed state.
This model is mostly characterized for its simplicity, requiring only two material constants determined through experimentation, making it practical for characterizing a wide range of materials. Even though its limitations are well known, it is still able to achieve good theoretical values for strains up to 150% [77]. It is also the most used throughout the reviewed articles, specifically the two parameter and five parameter Mooney-Rivlin models.

- **Ogden model:**
Introduced by Ogden [81] it is characterized by its versatility, being capable of matching recorded data throughout a wide range of strains. The strain energy density function is as follows [82]:

$$W = \sum_{i=1}^{N} \frac{\mu_1}{\alpha_1}(\lambda_1^{\alpha_1} + \lambda_2^{\alpha_2} + \lambda_3^{\alpha_3} - 3) \quad (3)$$

where $\lambda_j, (j = 1, 2, 3)$ is the main stretch ratio, and μ_i and α_i are material parameters.
It is one of the most used in rubber-like material modeling, such as O-rings and seals, being capable of agreeing with test data up to 700% of the tensile test results. It has been also widely implemented in soft robotics FEM, being extensively used in compliant mechanisms planning.

- **Neo-Hookean model:**
Proposed by Rivlin [79] as a special case of the Mooney-Rivlin form of strain energy function when $C_2 = 0$:

$$W = C_1(\bar{I}_1 - 3) \quad (4)$$

where C_1 is a material constant, and $\bar{I}_1$ is the first invariant associated with the deformed state.
Unlike linear elastic materials, a Neo-Hookean material exhibits a nonlinear stress-strain curve. Initially, the relationship between applied stress and strain is linear, but beyond a certain point, the stress-strain curve levels off. The Neo-Hookean model does not consider the dissipation of energy as heat during material straining, and it assumes perfect elasticity throughout all stages of deformation.

Even though the Ogden model is one of the most accurate when dealing with large deformation (Fig. 7), the Neo-Hookean and Mooney-Rivlin models are still widely used due to their simplicity and ease of use [10], [22], [23], [30]. In addition, these models offer other advantages that contribute to their widespread adoption in gripper design and control. Their computational efficiency allows for faster simulations and real-time control, which is essential in applications where rapid responses are required. Their versatility extends beyond grippers to various fields, including robotics, biomedical devices, and material science, further solidifying their role as convenient and reliable tools for engineers and researchers seeking effective solutions for compliant and deformable materials.

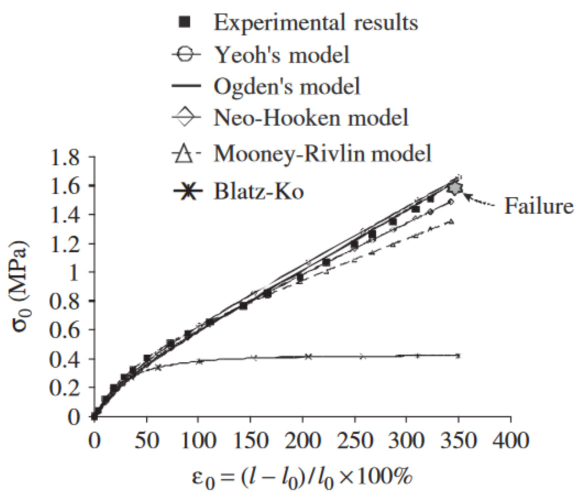


FIGURE 7. Model representation of experimental data by various models [77].

C. ACTUATION METHODS

Soft grippers produced through 3D printing feature compliant and deformable structures, providing enhanced adaptability. However, their ability to achieve precise and adaptable movements relies heavily on effective actuation methods. Consequently, the selection of the actuation method plays a crucial role in determining the gripper's capabilities and performance (Fig. 8). This section inquires into the various actuation methods employed in the 3D printed soft grippers presented in the reviewed articles (Table 6), each of which offers unique advantages and allows these grippers to operate successfully in tasks that demand delicate object handling or complex manipulation.

In order to properly categorize all the actuation methods reviewed, only the last external stimuli received by the gripper have been taken into account. For instance, even though a motor could manipulate a finger through a cable, it has been categorized as cable driven. Following this criterion, the subsequent categories have been determined:

- **Pneumatic actuation:**
The soft gripper is actuated by pumping air directly into its actuators [44]. This is a commonly used method due to the ease and speed of designing and manufacturing 3D printed soft actuators. These actuators often resemble bellows and frequently employ origami principles to achieve complex movements through applied pneumatic force. There are two common approaches: the actuators

TABLE 6. Analysis on reviewed actuation methods for 3D printed soft grippers.

Actuation	Bibliography	References
 Pneumatic	15	[10], [21]–[23], [28]–[30], [33], [35]–[40], [44]
 Motor	10	[11], [12], [16]–[19], [24], [25], [27], [42]
 Cable	7	[13], [15], [20], [26], [32], [34], [41]
 Temperature	3	[14], [31], [45]
 Magnetic	1	[43]

can be connected to the final grasping part to facilitate movement, or they can be seamlessly integrated into the design of the grasping element itself. The latter type of actuator relies on the deformation resulting from the expansion of the air ducts to interact with the target object.

An illustrative example is presented by Tawk et al. [10], where they created a 3D printed modular soft gripper integrated with metamaterials for conformal grasping. This gripper used pressurized air to achieve the desired deformation and grasping force, previously optimized through the use of finite element modeling.

The use of pneumatic actuation ensures a gentle and precise operation of the soft gripper, resulting in a damage-free interaction with the object.

- **Motor driven:**
  The main actuation force is achieved by a motor, directly applying movement onto the gripper [11]. For this categorization, it is still recognized as ''motor driven'' if the force is applied through gears, a threaded rod or any other solid mechanical link. On the other hand, if the motor's force is applied through a cable or any other non-solid link, it is not recognized in this group. This type of actuation usually offers the highest grip force, allowing the gripper to handle higher loads. This is demonstrated by Sun, et al. [42], who developed a lightweight robotic gripper with 3D topology-optimized adaptive fingers capable of handling payloads of 8.8 kg. The linear motor used to actuate the gripper was capable of generating an output force of 64N at zero-speed. In this type of actuated grippers, the force achieved is greater than with any other actuation method (considering 3D printed soft grippers), as shown in the reviewed articles.
  Motor actuation offers advantages in terms of accuracy, speed, and force, and it is often preferred when a high degree of dexterity, repeatability, and control is required for tasks like pick-and-place operations, assembly, and material handling.
- **Cable driven:**
  Typically used with grippers composed of fingers. It works by applying tension to the cable by means of a motor or other similar actuation method [41]. The length of cable inside the finger shortens, forcing it to bend in that particular direction. A composition of cables can be used to allow movement in more than 2 axis, enabling more complex manipulations and better overall control of the gripper [34].
  A combination of compliant mechanisms and cable actuation can also be implemented, allowing a much simpler and precise control of the gripper's movements [20].
  An excellent example is provided by Goh et al. [83]. In their article, the design and manufacturing of a 3D printed-enabled artificially innervated smart soft gripper with variable joint stiffness is proposed. The use of 3D multi-material printing enhances the gripping strength and enables various grasping modes while maintaining the same actuation characteristics. The simple cable driven actuation in the soft gripper facilitates customization in the manufacturing process.
- **Temperature driven:**
  These grippers are designed for use with 4D materials and Shape Memory Polymers (SMP) [45]. During the manufacturing process, each part of the gripper is made from different materials, depending on the desired final deformation. When temperature variations are applied to the gripper, these materials respond by expanding or contracting at different rates, causing the gripper to change shape as previously designed. This makes this type of gripper a valuable asset, as no external actuation is required and can respond autonomously to stimuli. This behaviour is illustrated by Yang and Chen [31]. In their article, a shape memory polymer (SMP) is proposed as the main actuator for the proposed finger design, highlighting the advantages of this type of drive, as it does not require any external force.
- **Magnetic actuation:**
  This type of actuation relies on the application of magnetic fields onto paramagnetic materials. These materials can be suspended in a flexible matrix during manufacturing, giving the overall gripper magnetic properties. When the magnetic field imposes a force on the gripper, it responds by deforming in a predictable way, as previously designed [43]. This type of actuation usually relies on the use of compliant mechanisms,

as well as 4D materials. The latter are also known as programmable materials [84] and allow 3D printed structures to change its configuration or function in response to external stimuli such as temperature, light, water, etc.

This type of actuation is presented by Shao et al. [43], who manufacture a magnetically driven micro-gripper through μCLIP technology and the use of suspended magnetic nanoparticles in a resin matrix. This article illustrates the principles of magnetic actuation applied at the microscale, showing the strengths of this type of actuation.

While there are relatively few examples of this type of actuation in soft robotics, it allows for precise manipulation at microscales where alternative actuation methods may be less effective [43].

V. CHALLENGES

It remains clear from this review that, although soft grippers are slowly being used more and more in robotics, 3D printed soft grippers are still far from extended use. This is mainly due to the lack of resources related with the design and manufacturing process of these soft grippers, as well as the inherent struggle in its control and actuation. Some of the main barriers and limitations that 3D printed soft grippers face nowadays against their extended application are listed below:

- Design process: one of the main challenges when producing 3D printed soft grippers is their design process. As they are usually based on compliant mechanisms, the prediction of their behaviour is quite challenging. Despite the huge advancements achieved in FEM in the last years, the hyper-elastic characteristics of these materials makes it difficult to model and simulate the gripper prior to its manufacturing, needing specific mathematical models depending on various factors, as seen in Section IV-B. It is also important to note that when designing with 3D printing in mind as a manufacturing method, the design process is quite different from the traditional design process. Various factors have to be taken into account when designing the final model. For instance, each AM technology has its own limitations: when 3D printing thin walls or small details, the temperature each materials requires, inner stresses during the manufacturing of a piece among others. Another key factor is to adapt the soft gripper's geometry depending on the AM technology used, for example, creating angled faces to avoid the need of support when using FDM technology.
- Standard method for the realization of grip tests: another main challenge that is not yet addressed in many of the reviewed articles, is the need of a proper method to characterize the gripping capability of each proposed design. There are many parameters that directly intervene in the gripper's performance, such as surface texture, applied pressure and contact area. Some articles, such as [10], [41], [43], [44], and [45], tend to demonstrate this performance by direct manipulation of basic geometries or using the YCB object set [85], proving its efficacy against various form factors. Others tend to use embedded sensors or other monitoring technology in order to analyze the force achieved during object manipulation [13], [19]. One last common approach is to use the so called payload test or pull-off test [12], [23], [25], [33], [42]. While these are two different tests, both are destined to determine the maximum load a gripper can manipulate. The first one usually employs basic geometries, to which incremental weights are added until the grip fails. The latter uses the same principle, but the force is measured through a force gauge and the maximum value is registered. Having a standard method to measure the performance of a gripper would not only allow to select the proper design for each application, but also providing a global picture in the evolution of this technology.
- Manufacturing cost: 3D printing is often referred to as a cheaper way of producing prototype models and functional parts. However, this tends to change when using softer materials. Fused Deposition Modeling (FDM) printers, the most commonly used type, demand specific components for soft materials and are limited to using filament formats up to a shore hardness of approximately 60A. When employing alternative technologies like PolyJet, the investment required significantly increases, encompassing both the printer itself and the soft materials. All these costs affect the price of the final model. While this is usually not a setback for prototype development or customized production, it becomes a critical consideration in industrial applications where higher production volumes are essential. Traditional manufacturing methods often present more cost-effective solutions, enabling the production of larger batches in less time. The cost of 3D printing technologies has also changed with recent advancements, making some of them more affordable. This is particularly important because, with proper research and development, 3D printing methods for soft grippers may not only rival traditional manufacturing processes but also provide additional value to the product by enabling new functionalities and applications.
- Limited resources: one significant challenge in the development of 3D printed soft grippers is the limited availability of resources. Although there is currently limited literature on this technology, it represents an opportunity for future research and innovation. Design and manufacturing processes for 3D printed soft grippers still remains a complex task due to the scarcity of comprehensive resources. Furthermore, there is a need for a broader base of knowledge relating to 3D printing. As previously mentioned, different 3D printing technologies require distinct design methodologies.

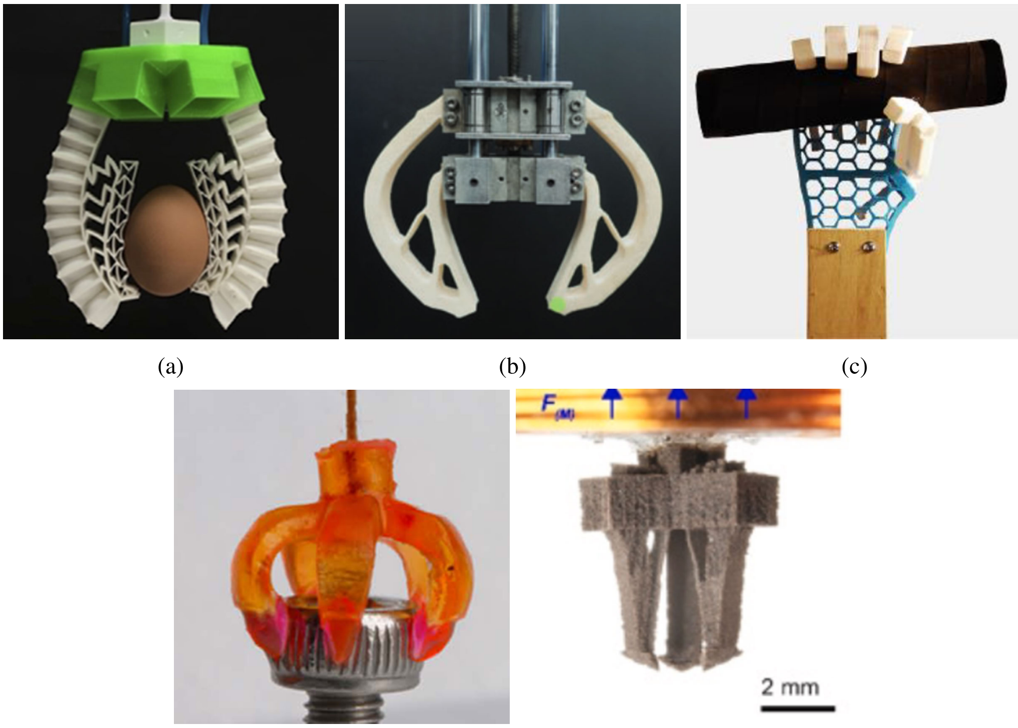


FIGURE 8. Classification of actuation methods for soft grippers. (a) Pneumatically actuated gripper [10], (b) Motor driven gripper [12], (c) Cable driven gripper [15], (d) Temperature driven gripper [45], (e) Magnetically actuated gripper [30].

Each additive manufacturing (AM) technique demands an unique understanding of its working principles, manufacturing parameters, and more. While the usage of 3D printing is expanding rapidly and becoming more prevalent, it's essential to recognize that this technology is still in its early stages of development and is continuously evolving. This evolution can pose challenges in keeping pace with the latest advancements. However, it's crucial to view this transformation as a promising aspect. The creation of new literature on the matter will provide comprehensive insight into the entire process, thereby facilitating progress in this field.

- Manufacturing process: 3D printing with soft materials is still relatively new, and as a result, the manufacturing processes and technology continue to evolve. One big obstacle when using soft materials is their handling and use. For example, as mentioned earlier, FDM printers often require specific components or special extruders, as well as adjusting printing parameters such as print speed or retraction speed and distance, to handle soft filaments or pellets for softer polymers. When using resin-based AM technologies, the high viscosity of these resins usually poses challenges in the printing process, leading to instability in the manufactured objects, often resulting in failed prints, poor surface quality, and tolerance issues. Other technologies have their own complications when using soft polymers, usually resulting in rejected models. Advancements in this field are still needed to simplify manufacturing processes, ultimately leading to better performance and more intricate designs.

VI. CONCLUSION

While 3D printing offers unique advantages in gripper manufacturing compared to traditional methods, it is still in continuous development. Many additive manufacturing (AM) technologies and their applications, especially in the robotics field, require a certain level of maturity and user experience to properly assess their potential and applications. The use of flexible materials in AM remains challenging, but each new advancement contributes to the improvement and establishment of this technology, enabling new design paths.

In this article, a detailed review of the latest advancements in soft gripper design and manufacturing employing AM technologies is presented. Firstly, the primary AM technologies employed in the production of these soft grippers are analyzed, aiming to enhance the understanding of the current state of this technology's development and its application. Additionally, it offers insight into new design approaches specific to these manufacturing methods, which often differ from traditional design methodologies. This analysis also encompasses the materials used in soft gripper manufacturing, exploring various technologies and their key characteristics.

Furthermore, some of the key geometries used in the design of the reviewed grippers are presented and evaluated.

This categorization is particularly relevant to this review, as it offers a global view of the main design approaches used with this kind of technology and materials. It is also important to note that traditional design approaches still prevail, as many of these grippers continue to use conventional design methods. However, while this approach may help establish AM usage, it limits the exploration of other possible AM-oriented designs. The article also includes a detailed analysis of the different mathematical models used to characterize hyper-elastic materials and the main actuation methods employed in these grippers.

Also, some of the main challenges that 3D printed soft grippers must overcome to establish their definitive implementation in robotics include the design process required for these new technologies, the need for a standard method to characterize the gripping capabilities of the end gripper, the manufacturing costs compared to large-scale traditional gripper production, the scarcity of resources available concerning AM technologies and AM-oriented design, and the manufacturing challenges encountered when working with flexible materials.

From this review, it is clear that there are still steps to be taken in soft robotics, and more particularly in its development through the use of additive manufacturing. The clear benefits that this technology brings to robotics, such as ease of fabrication, low cost, simplicity and complex soft actuator design are promising assets. Therefore, future research lines should be directed to developing standardized protocols to adequately characterize each gripper, such as grip tests. This standardized approach will facilitate the proper evaluation of gripper performance, design, and manufacturing. Moreover, new materials should be researched and tested for gripper manufacturing through Additive Manufacturing (AM) technologies. Materials like self-healing polymers [86] are of great importance, offering new functionalities and allowing robots to operate in harsh and unstructured environments. Ultra-soft polymers are also in need of development as a manufacturing element, being a recent trend within pellet based FDM and SLS technologies, allowing better adaptability to different scenarios. Additionally, incorporating passive intake designs, a well established concept in rigid robotics, could prove beneficial. These can be designed for and specific task and object, allowing precise manipulation without the need of complex actuation systems. Lastly, the implementation of soft tools should also be taken into consideration. These can offer the same lever of dexterity and precision while introducing capabilities related to soft robotics, without alterations to the manipulator's end-effector: they can be adapted onto existing rigid components.

REFERENCES

[1] ASTM Committee F42 on Additive Manufacturing Technologies and ASTM Committee F42 on Additive Manufacturing Technologies. Subcommittee F42. 91 on Terminology, *Standard Terminology for Additive Manufacturing Technologies*, ASTM International, 2012.

[2] J. Shintake, V. Cacucciolo, D. Floreano, and H. Shea, "Soft robotic grippers," *Adv. Mater.*, vol. 30, no. 29, Jul. 2018, Art. no. 1707035.

[3] S. Perai, "Methodology of compliant mechanisms and its current developments in applications: A review," *Amer. J. Appl. Sci.*, vol. 4, no. 3, pp. 160–167, Mar. 2007.

[4] S. Kim, C. Laschi, and B. Trimmer, "Soft robotics: A bioinspired evolution in robotics," *Trends Biotechnol.*, vol. 31, no. 5, pp. 287–294, May 2013.

[5] J. A. Gallego and J. Herder, "Synthesis methods in compliant mechanisms: An overview," in *Proc. Int. Design Eng. Tech. Conf. Comput. Inf. Eng. Conf.*, vol. 49040, 2009, pp. 193–214.

[6] E. Sachyani Keneth, A. Kamyshny, M. Totaro, L. Beccai, and S. Magdassi, "3D printing materials for soft robotics," *Adv. Mater.*, vol. 33, no. 19, May 2021, Art. no. 2003387.

[7] G. D. Goh, G. L. Goh, Z. Lyu, M. Z. Ariffin, W. Y. Yeong, G. Z. Lum, D. Campolo, B. S. Han, and H. Y. A. Wong, "3D printing of robotic soft grippers: Toward smart actuation and sensing," *Adv. Mater. Technol.*, vol. 7, no. 11, Nov. 2022, Art. no. 2101672.

[8] Y. Xin, X. Zhou, H. Bark, and P. S. Lee, "The role of 3D printing technologies in soft grippers," *Adv. Mater.*, Dec. 2023, Art. no. 2307963.

[9] T. J. Wallin, J. Pikul, and R. F. Shepherd, "3D printing of soft robotic systems," *Nature Rev. Mater.*, vol. 3, no. 6, pp. 84–100, May 2018.

[10] C. Tawk, R. Mutlu, and G. Alici, "A 3D printed modular soft gripper integrated with metamaterials for conformal grasping," *Frontiers Robot. AI*, vol. 8, Jan. 2022, Art. no. 799230.

[11] P. Matos and P. Neto, "A 3D-printable modular robotic gripper," *Int. J. Adv. Manuf. Technol.*, vol. 126, nos. 1–2, pp. 845–855, May 2023.

[12] C.-H. Liu, T.-L. Chen, C.-H. Chiu, M.-C. Hsu, Y. Chen, T.-Y. Pai, W.-G. Peng, and Y.-P. Chiang, "Optimal design of a soft robotic gripper for grasping unknown objects," *Soft Robot.*, vol. 5, no. 4, pp. 452–465, Aug. 2018.

[13] M. Kaur and W. S. Kim, "Toward a smart compliant robotic gripper equipped with 3D-designed cellular fingers," *Adv. Intell. Syst.*, vol. 1, no. 3, Jul. 2019, Art. no. 1900019.

[14] A. Zolfagharian, M. Lakhi, S. Ranjbar, M. Sayah Irani, M. Nafea, and M. Bodaghi, "4D printing parameters optimisation for bi-stable soft robotic gripper design," *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 45, no. 4, p. 224, Apr. 2023.

[15] A. Orabona, A. Palazzi, S. Graziosi, F. Ferrise, and M. Bordegoni, "Design of a simplified 3D-printed artificial underactuated hand," in *Proc. Design Soc., Design Conf.*, vol. 1, 2020, pp. 1027–1036.

[16] C.-H. Liu and P.-T. Hung, "Effect of the infill density on the performance of a 3D-printed compliant finger," *Mater. Design*, vol. 223, Nov. 2022, Art. no. 111203.

[17] A. Georgopoulou and F. Clemens, "Pellet-based fused deposition modeling for the development of soft compliant robotic grippers with integrated sensing elements," *Flexible Printed Electron.*, vol. 7, no. 2, Jun. 2022, Art. no. 025010.

[18] C.-H. Liu, Y. Chen, and S.-Y. Yang, "Topology optimization and prototype of a multimaterial-like compliant finger by varying the infill density in 3D printing," *Soft Robot.*, vol. 9, no. 5, pp. 837–849, Oct. 2022.

[19] C.-H. Liu, F.-M. Chung, and Y.-P. Ho, "Topology optimization for design of a 3D-printed constant-force compliant finger," *IEEE/ASME Trans. Mechatronics*, vol. 26, no. 4, pp. 1828–1836, Aug. 2021.

[20] R. Wang, X. Zhang, B. Zhu, H. Zhang, B. Chen, and H. Wang, "Topology optimization of a cable-driven soft robotic gripper," *Structural Multidisciplinary Optim.*, vol. 62, no. 5, pp. 2749–2763, Nov. 2020.

[21] H. M. C. M. Anver, R. Mutlu, and G. Alici, "3D printing of a thin-wall soft and monolithic gripper using fused filament fabrication," in *Proc. IEEE Int. Conf. Adv. Intell. Mechtron. (AIM)*, Jul. 2017, pp. 442–447.

[22] R. Mutlu, C. Tawk, G. Alici, and E. Sariyildiz, "A 3D printed monolithic soft gripper with adjustable stiffness," in *Proc. IECON 43rd Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2017, pp. 6235–6240.

[23] C. Tawk, A. Gillett, M. I. H. Panhuis, G. M. Spinks, and G. Alici, "A 3D-printed omni-purpose soft gripper," *IEEE Trans. Robot.*, vol. 35, no. 5, pp. 1268–1275, Oct. 2019.

[24] C.-H. Liu, C.-H. Chiu, T.-L. Chen, T.-Y. Pai, Y. Chen, and M.-C. Hsu, "A soft robotic gripper module with 3D printed compliant fingers for grasping fruits," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2018, pp. 736–741.

[25] C.-H. Liu, M.-C. Hsu, Y. Chen, W.-T. Chen, and T.-L. Chen, "A topology-optimized 3D printed compliant finger with flex sensor for adaptive grasping of unknown objects," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2019, pp. 92–97.

[26] L. Y. Lee, S. G. Nurzaman, and C. P. Tan, "Design and analysis of a gripper with interchangeable soft fingers for ungrounded mobile robots," in *Proc. IEEE Int. Conf. Cybern. Intell. Syst. (CIS) IEEE Conf. Robot., Autom. Mechatronics (RAM)*, Nov. 2019, pp. 221–226.

[27] C.-H. Liu, T.-L. Chen, T.-Y. Pai, C.-H. Chiu, W.-G. Peng, and M.-C. Hsu, "Topology synthesis, prototype, and test of an industrial robot gripper with 3D printed compliant fingers for handling of fragile objects," in *Proc. WRC Symp. Adv. Robot. Autom. (WRC SARA)*, Aug. 2018, pp. 189–194.
[28] C. Tawk, R. Mutlu, and G. Alici, "A3D printed modular soft gripper for conformal grasping," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechtron. (AIM)*, Jul. 2020, pp. 583–588.
[29] J. H. Low, W. W. Lee, P. M. Khin, N. V. Thakor, S. L. Kukreja, H. L. Ren, and C. H. Yeow, "Hybrid tele-manipulation system using a sensorized 3-D-printed soft robotic gripper and a soft fabric-based haptic glove," *IEEE Robot. Autom. Lett.*, vol. 2, no. 2, pp. 880–887, Apr. 2017.
[30] C. Tawk, Y. Gao, R. Mutlu, and G. Alici, "Fully 3D printed monolithic soft gripper with high conformal grasping capability," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechtron. (AIM)*, Jul. 2019, pp. 1139–1144.
[31] Y. Yang and Y. Chen, "Novel design and 3D printing of variable stiffness robotic fingers based on shape memory polymer," in *Proc. 6th IEEE Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Jun. 2016, pp. 195–200.
[32] J. Nichols Cook, A. Sabarwal, H. Clewer, and W. Navaraj, "Tactile sensor array laden 3D-printed soft robotic gripper," in *Proc. IEEE SENSORS*, Oct. 2020, pp. 1–4.
[33] G. D. Howard, J. Brett, J. O'Connor, J. Letchford, and G. W. Delaney, "One-shot 3D-printed multimaterial soft robotic jamming grippers," *Soft Robot.*, vol. 9, no. 3, pp. 497–508, Jun. 2022.
[34] K. Lee, Y. Wang, and C. Zheng, "TWISTER hand: Underactuated robotic gripper inspired by origami twisted tower," *IEEE Trans. Robot.*, vol. 36, no. 2, pp. 488–500, Apr. 2020.
[35] Z. Wang, D. S. Chathuranga, and S. Hirai, "3D printed soft gripper for automatic lunch box packing," in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Dec. 2016, pp. 503–508.
[36] Z. Wang and S. Hirai, "A 3D printed soft gripper integrated with curvature sensor for studying soft grasping," in *Proc. IEEE/SICE Int. Symp. Syst. Integr. (SII)*, Dec. 2016, pp. 629–633.
[37] Z. Wang, Y. Torigoe, and S. Hirai, "A prestressed soft gripper: Design, modeling, fabrication, and tests for food handling," *IEEE Robot. Autom. Lett.*, vol. 2, no. 4, pp. 1909–1916, Oct. 2017.
[38] J. Pinskier, P. Kumar, M. Langelaar, and D. Howard, "Automated design of pneumatic soft grippers through design-dependent multi-material topology optimization," in *Proc. IEEE Int. Conf. Soft Robot. (RoboSoft)*, Apr. 2023, pp. 1–7.
[39] M. Zhu, Y. Mori, M. Xie, A. Wada, and S. Kawamura, "A 3D printed two DoF soft robotic finger with variable stiffness," in *Proc. 12th France-Japan 10th Eur.-Asia Congr. Mechtron.*, Japan, Sep. 2018, pp. 387–391.
[40] Y. Makiyama, Z. Wang, and S. Hirai, "A pneumatic needle gripper for handling shredded food products," in *Proc. IEEE Int. Conf. Real-Time Comput. Robot. (RCAR)*, Sep. 2020, pp. 183–187.
[41] Y. Yang, K. Jin, H. Zhu, G. Song, H. Lu, and L. Kang, "A 3D-printed fin ray effect inspired soft robotic gripper with force feedback," *Micromachines*, vol. 12, no. 10, p. 1141, Sep. 2021.
[42] Y. Sun, Y. Liu, F. Pancheri, and T. C. Lueth, "LARG: A lightweight robotic gripper with 3-D topology optimized adaptive fingers," *IEEE/ASME Trans. Mechatronics*, vol. 27, no. 4, pp. 2026–2034, Aug. 2022.
[43] G. Shao, H. O. T. Ware, J. Huang, R. Hai, L. Li, and C. Sun, "3D printed magnetically-actuating micro-gripper operates in air and water," *Additive Manuf.*, vol. 38, Feb. 2021, Art. no. 101834.
[44] A. Koivikko, D.-M. Drotlef, C. B. Dayan, V. Sariola, and M. Sitti, "3D-printed pneumatically controlled soft suction cups for gripping fragile, small, and rough objects," *Adv. Intell. Syst.*, vol. 3, no. 9, Sep. 2021, Art. no. 2100034.
[45] Q. Ge, A. H. Sakhaei, H. Lee, C. K. Dunn, N. X. Fang, and M. L. Dunn, "Multimaterial 4D printing with tailorable shape memory polymers," *Sci. Rep.*, vol. 6, no. 1, p. 31110, Aug. 2016.
[46] Stratasys. *FDM 3D Printing—Fused Deposition Modeling*. Accessed: Aug. 28, 2023. [Online]. Available: https://www.stratasys.com/en/guide-to-3d-printing/technologies-and-materials/fdm-technology/
[47] X. Wan, L. Luo, Y. Liu, and J. Leng, "Direct ink writing based 4D printing of materials and their applications," *Adv. Sci.*, vol. 7, no. 16, Aug. 2020, Art. no. 2001000.
[48] M. A. S. R. Saadi, A. Maguire, N. T. Pottackal, M. S. H. Thakur, M. M. Ikram, A. J. Hart, P. M. Ajayan, and M. M. Rahman, "Direct ink writing: A 3D printing technology for diverse materials," *Adv. Mater.*, vol. 34, no. 28, Jul. 2022, Art. no. 2108855.
[49] T. Ching, Y. Li, R. Karyappa, A. Ohno, Y.-C. Toh, and M. Hashimoto, "Fabrication of integrated microfluidic devices by direct ink writing (DIW) 3D printing," *Sens. Actuators B, Chem.*, vol. 297, Oct. 2019, Art. no. 126609.
[50] L. Li, Q. Lin, M. Tang, A. J. E. Duncan, and C. Ke, "Frontispiece: Advanced polymer designs for direct-ink-write 3D printing," *Chem. A Eur. J.*, vol. 25, no. 46, pp. 10768–10781, Aug. 2019.
[51] Y. Zhang, G. Shi, J. Qin, S. E. Lowe, S. Zhang, H. Zhao, and Y. L. Zhong, "Recent progress of direct ink writing of electronic components for advanced wearable devices," *ACS Appl. Electron. Mater.*, vol. 1, no. 9, pp. 1718–1734, Sep. 2019.
[52] Materialise. *Polyjet*. Accessed: Sep. 27, 2023. [Online]. Available: https://www.materialise.com/es/industrial/tecnologias-impresion-3d/polyjet
[53] D. Yan, J. Chang, H. Zhang, J. Liu, H. Song, Z. Xue, F. Zhang, and Y. Zhang, "Soft three-dimensional network materials with rational bio-mimetic designs," *Nature Commun.*, vol. 11, no. 1, p. 1180, Mar. 2020.
[54] N. Kastor, V. Vikas, E. Cohen, and R. D. White, "A definition of soft materials for use in the design of robots," *Soft Robot.*, vol. 4, no. 3, pp. 181–182, Sep. 2017.
[55] Dassault Systemes. *TPE Vs. TPU: Differences and Comparison*. Accessed: Dec. 19, 2023. [Online]. Available: https://www.3ds.com/make/solutions/blog/tpe-vs-tpu-differences-and-comparison
[56] F. Momeni, X. Liu, and J. Ni, "A review of 4D printing," *Mater. Design*, vol. 122, pp. 42–79, May 2017.
[57] Z. X. Khoo, J. E. M. Teoh, Y. Liu, C. K. Chua, S. Yang, J. An, K. F. Leong, and W. Y. Yeong, "3D printing of smart materials: A review on recent progresses in 4D printing," *Virtual Phys. Prototyping*, vol. 10, no. 3, pp. 103–122, Jul. 2015.
[58] A. S. Gladman, E. A. Matsumoto, R. G. Nuzzo, L. Mahadevan, and J. A. Lewis, "Biomimetic 4D printing," *Nature Mater.*, vol. 15, no. 4, pp. 413–418, Apr. 2016.
[59] J. Flynt. *What is Powder-Based 3D Printing?*. Accessed: Dec. 19, 2023. [Online]. Available: https://3dinsider.com/powder-based-3d-printing/
[60] H. C. Greenberg, M. L. Gong, S. P. Magleby, and L. L. Howell, "Identifying links between origami and compliant mechanisms," *Mech. Sci.*, vol. 2, no. 2, pp. 217–225, Dec. 2011.
[61] M. D. Murphy, A. Midha, and L. L. Howell, "The topological synthesis of compliant mechanisms," *Mechanism Mach. Theory*, vol. 31, no. 2, pp. 185–199, Feb. 1996.
[62] L. L. Howell, S. P. Magleby, and B. M. Olsen, *Handbook of Compliant Mechanisms*. Hoboken, NJ, USA: Wiley, 2013.
[63] L. Yin and G. K. Ananthasuresh, "Design of distributed compliant mechanisms," *Mech. Based Design Struct. Mach.*, vol. 31, no. 2, pp. 151–179, Jan. 2003.
[64] T. Yamada, K. Izui, S. Nishiwaki, and A. Takezawa, "A topology optimization method based on the level set method incorporating a fictitious interface energy," *Comput. Methods Appl. Mech. Eng.*, vol. 199, nos. 45–48, pp. 2876–2891, Nov. 2010.
[65] M. P. Bendsoe and O. Sigmund, *Topology Optimization: Theory Methods, and Applications*. Berlin, Germany: Springer, 2003.
[66] E. Brown, N. Rodenberg, J. Amend, A. Mozeika, E. Steltz, M. R. Zakin, H. Lipson, and H. M. Jaeger, "Universal robotic gripper based on the jamming of granular material," *Proc. Nat. Acad. Sci. USA*, vol. 107, no. 44, pp. 18809–18814, Nov. 2010.
[67] D. Howard, J. O'Connor, J. Brett, and G. W. Delaney, "Shape, size, and fabrication effects in 3D printed granular jamming grippers," in *Proc. IEEE 4th Int. Conf. Soft Robot. (RoboSoft)*, Apr. 2021, pp. 458–464.
[68] J. R. Amend, E. Brown, N. Rodenberg, H. M. Jaeger, and H. Lipson, "A positive pressure universal gripper based on the jamming of granular material," *IEEE Trans. Robot.*, vol. 28, no. 2, pp. 341–350, Apr. 2012.
[69] B. Mazzolai, A. Mondini, F. Tramacere, G. Riccomi, A. Sadeghi, G. Giordano, E. Del Dottore, M. Scaccia, M. Zampato, and S. Carminati, "Octopus-inspired soft arm with suction cups for enhanced grasping tasks in confined environments," *Adv. Intell. Syst.*, vol. 1, no. 6, Oct. 2019, Art. no. 1900041.
[70] Z. Zhakypov, F. Heremans, A. Billard, and J. Paik, "An origami-inspired reconfigurable suction gripper for picking objects with variable shape and size," *IEEE Robot. Autom. Lett.*, vol. 3, no. 4, pp. 2894–2901, Oct. 2018.
[71] *Schmalz*. Accessed: Oct. 3, 2023. [Online]. Available: https://www.schmalz.com/en/vacuum-technology-for-automation/industries-and-applications/cleanroom/
[72] A. K. Jaiswal and B. Kumar, "Vacuum gripper—An important material handling tool," *Int. J. Sci. Technol.*, vol. 7, no. 1, pp. 1–8, 2017.
[73] A. R. Torrado, C. M. Shemelya, J. D. English, Y. Lin, R. B. Wicker, and D. A. Roberson, "Characterizing the effect of additives to ABS on the mechanical property anisotropy of specimens fabricated by material extrusion 3D printing," *Additive Manuf.*, vol. 6, pp. 16–29, Apr. 2015.

[74] G. Ma, Z. Li, L. Wang, F. Wang, and J. Sanjayan, "Mechanical anisotropy of aligned fiber reinforced composite for extrusion-based 3D printing," *Construct. Building Mater.*, vol. 202, pp. 770–783, Mar. 2019.

[75] M. R. Khosravani, S. Rezaei, H. Ruan, and T. Reinicke, "Fracture behavior of anisotropic 3D-printed parts: Experiments and numerical simulations," *J. Mater. Res. Technol.*, vol. 19, pp. 1260–1270, Jul. 2022.

[76] M. Somireddy, A. Czekanski, and C. V. Singh, "Development of constitutive material model of 3D printed structure via FDM," *Mater. Today Commun.*, vol. 15, pp. 143–152, Jun. 2018.

[77] A. P. S. Selvadurai, "Deflections of a rubber membrane," *J. Mech. Phys. Solids*, vol. 54, no. 6, pp. 1093–1119, Jun. 2006.

[78] M. Mooney, "A theory of large elastic deformation," *J. Appl. Phys.*, vol. 11, no. 9, pp. 582–592, Sep. 1940.

[79] R. S. Rivlin, "Large elastic deformations of isotropic materials iv. further developments of the general theory," *Phil. Trans. Roy. Soc. London. Ser. A, Math. Phys. Sci.*, vol. 241, no. 835, pp. 379–397, 1948.

[80] H. Menderes and A. W. Konter, "Advanced Fe analysis of elastomeric automobile components under realistic loading conditions," in *Proc. 1st Eur. Conf. Constitutive Models Rubber*, 1999, pp. 3–12.

[81] R. W. Ogden, "Large deformation isotropic elasticity—On the correlation of theory and experiment for incompressible rubberlike solids," *Proc. Roy. Soc. London. A, Math. Phys. Sci.*, vol. 326, no. 1567, pp. 565–584, 1972.

[82] B. Kim, S. B. Lee, J. Lee, S. Cho, H. Park, S. Yeom, and S. H. Park, "A comparison among Neo-Hookean model, Mooney-Rivlin model, and Ogden model for chloroprene rubber," *Int. J. Precis. Eng. Manuf.*, vol. 13, no. 5, pp. 759–764, May 2012.

[83] G. L. Goh, G. D. Goh, V. P. Nguyen, W. Toh, S. Lee, X. Li, B. D. Sunil, J. Y. Lim, Z. Li, A. K. Sinha, W. Y. Yeong, D. Campolo, W. T. Chow, T. Y. Ng, and B. S. Han, "A 3D printing-enabled artificially innervated smart soft gripper with variable joint stiffness," *Adv. Mater. Technol.*, vol. 8, no. 24, Dec. 2023, Art. no. 2301426.

[84] S. Tibbits, "4D printing: Multi-material shape change," *Architectural Design*, vol. 84, no. 1, pp. 116–121, Jan. 2014.

[85] B. Calli, A. Singh, A. Walsman, S. Srinivasa, P. Abbeel, and A. M. Dollar, "The YCB object and model set: Towards common benchmarks for manipulation research," in *Proc. Int. Conf. Adv. Robot. (ICAR)*, Jul. 2015, pp. 510–517.

[86] S. Wang and M. W. Urban, "Self-healing polymers," *Nature Rev. Mater.*, vol. 5, no. 8, pp. 562–583, 2020.

KAI BLANCO recieved the B.S. degree in industrial design and product development engineering from Universidad Politécnica de Madrid, in 2020, and the M.S. degree in 3D printing and advanced manufacturing from Escuela de Diseño Mecánico, Madrid, in 2021. From 2020 to 2022, she worked in industries, such as aerospace and defense, where she contributed to the implementation of advanced manufacturing processes. Notably, she played a key role with Instituto Nacional de Técnica Aeroespacial (Torrejón de Ardoz), where she worked on the development of lightweight sabot for use in high-speed cannons for impact testing. In 2023, she joined the Center for Automation and Robotics, CSIC-UPM, as a Researcher. Currently, she is actively engaged in the development of soft robotics, focusing on the creation and control of soft tools. She is the author/coauthor of two papers published in scientific journals and conference proceedings. Her research interests include the utilization of additive manufacturing, mechanical design, and industrial production automation.

EDUARDO NAVAS received the B.S. degree in mechanical engineering from the University of Castilla-La Mancha, Spain, in 2017, and the M.Sc. degree in industrial engineering from the University of Valladolid, Spain, in 2019. He is currently pursuing the Ph.D. degree in systems engineering, automation, and robotics with the University of Valladolid, Spain. From 2018 to 2019, he was a Researcher with the Social System Engineering Centre (INSISOC), University of Valladolid. He worked on a project about agent-based modeling, railway slot allocation, and combinatorial auctions—ABARNET. In 2019, he joined Centre for Automation and Robotics (CAR), CSIC-UPM, as a Researcher. In this role, he actively engages in projects related to the design and development of dual manipulators and robotic field systems. Additionally, he has been actively involved in robotics projects, such as Robocity2023 and RoboCrop, which focus on intelligent sensing and dual-arm robotic manipulation for the selective harvesting of high-value crops. He has authored or coauthored 17 papers published in scientific journals and conference proceedings. His current research interests include the design of field robotic systems, soft robotics, and innovative robotic applications in industry and service.

LUIS EMMI received the B.E. degree in electronic engineering from Simón Bolívar University, Caracas, Venezuela, in 2008, and the M.E. degree in computer science specializing in engineering for industry and the Ph.D. degree in computer engineering (with mention of a European doctorate) from the University Complutense of Madrid (UCM), in 2011 and 2014, respectively. Currently, he is a Postdoctoral Researcher with the Center for Automation and Robotics (CAR), CSIC-UPM. His research interests include mobile robot navigation in open environments, manipulation robotics, mobile service robotics, architecture and control systems of multi-robot systems, and localization and guidance of autonomous robots using artificial intelligence techniques.

ROEMI FERNÁNDEZ received the Ph.D. degree in industrial engineering from the Polytechnic University of Madrid (ETSII-UPM), in 2006. She was a Visiting Ph.D. Student with the Center for Control Engineering and Computation, University of California at Santa Barbara, in 2003, and the Department of Automatic Control, Lund University, in 2004. From 2005 to 2009, she was an Associate Professor with San Pablo CEU University. She has also collaborated as a Professor of automation and robotics with ETSII-UPM. She is currently a Senior Scientist with the Centre for Automation and Robotics, CSIC-UPM. She has been working on 30 research projects (11 EU-funded projects) and six projects with private entities. She is the author of 11 patents and has published over 70 papers in scientific journals and conference proceedings. Her research interests include the design and control of field and service robotic systems, dual-arm robotic manipulation systems, intelligent perception and multisensory systems, and the design of non-linear actuators and non-linear controllers. She received the Award for Best Teaching, in 2008. She has served as an Expert Evaluator of the Executive Research Agency of the European Commission and the Spanish State Research Agency and a reviewer of several foreign research agencies and a large number of scientific journals and international conferences.