A Literature Review of Additive Manufacturing in the Fabrication of Soft Robots: Main Techniques, Applications, and Related Industrial-Sized Machines

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Soft robots have been receiving unprecedented attention in recent years for being able to be used side-by-side with humans, exploring dangerous environments and confined spaces, moving across uneven terrain, and solving problems that rigid robots cannot solve. The wide range of additive manufacturing techniques has also boosted research in the area. This work summarizes the characteristics of the five most relevant techniques – FDM, DIW, SLS, Inkjet, and SLA – for fabricating soft robots together with case studies. A summary contains models of industrial-sized additive manufacturing machines that can compose a facility for fabricating large-scale soft robots.

Keywords: Additive Manufacturing. 3D Printing. BiLi Method. Manufacturing Techniques. Soft Robots.

Introduction

Traditional robotics uses hard materials that allow robots to be precise but limit their ability to deform elastically and closely interact with the environment. Soft robots are the next generation of robots – made of soft and deformable materials – capable of safely cooperating with humans, steering through narrow spaces, and performing tasks that complex robots cannot do [1].

Several methods have been used to manufacture soft robots, but additive manufacturing (AM) stands out due to its versatility, especially regarding materials and techniques. AM can act on three levels in a soft robot project: rapid mold fabrication, hybrid approach, and total additive manufacturing. The latter is, however, the only one that takes full advantage of AM capabilities [2].

Fused deposition modeling, direct ink writing, selective laser sintering, inkjet printing, and stereolithography are the main techniques covered by the AM reviews aimed at soft robot fabrication [1-5]. However, to our knowledge, no review depicts the techniques and models of industrial-sized commercial 3D printing machines and their corresponding capacities, such as printable materials and build volume. Thus, this paper also aims to bring this information to the literature.

We organized this documents in sections: Introduction, Materials Methods, which presents the method used to gather and extract information of the main works on the theme; the Additive Manufacturing in Soft Robots that details the characteristics of each manufacturing technique, along with examples in soft robots and commercial machine models, and the Conclusion that closes this study.

Materials and Methods

The review was based on three steps: mining scientific articles, identifying the main AM techniques applied in soft robots, and surveying related industrial machinery.

The BiLi method [6] was used in the first step for collecting and mining scientific articles. The method requires iterative search strings to filter relevant candidate works for evaluation. As a result, it allowed a significant reduction in the number of documents for reading and analysis in this review - from 1,136 to 28.

The second step consisted of parsing the collection of works to map the main AM techniques used for soft robot fabrication according to the following criteria:

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- Application in soft robot fabrication.
- Occurrences within the scientific works.

The last step consisted of listing industrial-sized AM machines corresponding to all techniques summarized in the previous step. The research sources for these machines comprised articles, manufacturer websites, and magazines. The selection used the following criteria:

- Large building volume.
- High market price.
- Consolidation of the manufacturer in the market (qualitatively assessed).

Figure 1 summarizes the method used in the study.

Additive Manufacturing in Soft Robots

The concept map shown in Figure 2 depicts the main ideas related to the theme "additive manufacturing in soft robots," as provided by the research conducted in Materials and Methdos Section. It showed that manufacturing in soft robots has four main fronts: role (rapid mold fabrication, hybrid approach, or total additive manufacturing), purpose (actuation or sensing), materials, and manufacturing techniques. The latter is the focus of this work, so the following subsections present the concepts of the main techniques, their applications in soft robots, and corresponding models of industrial-sized commercial machines.

Figure 1. Summary of the used method.

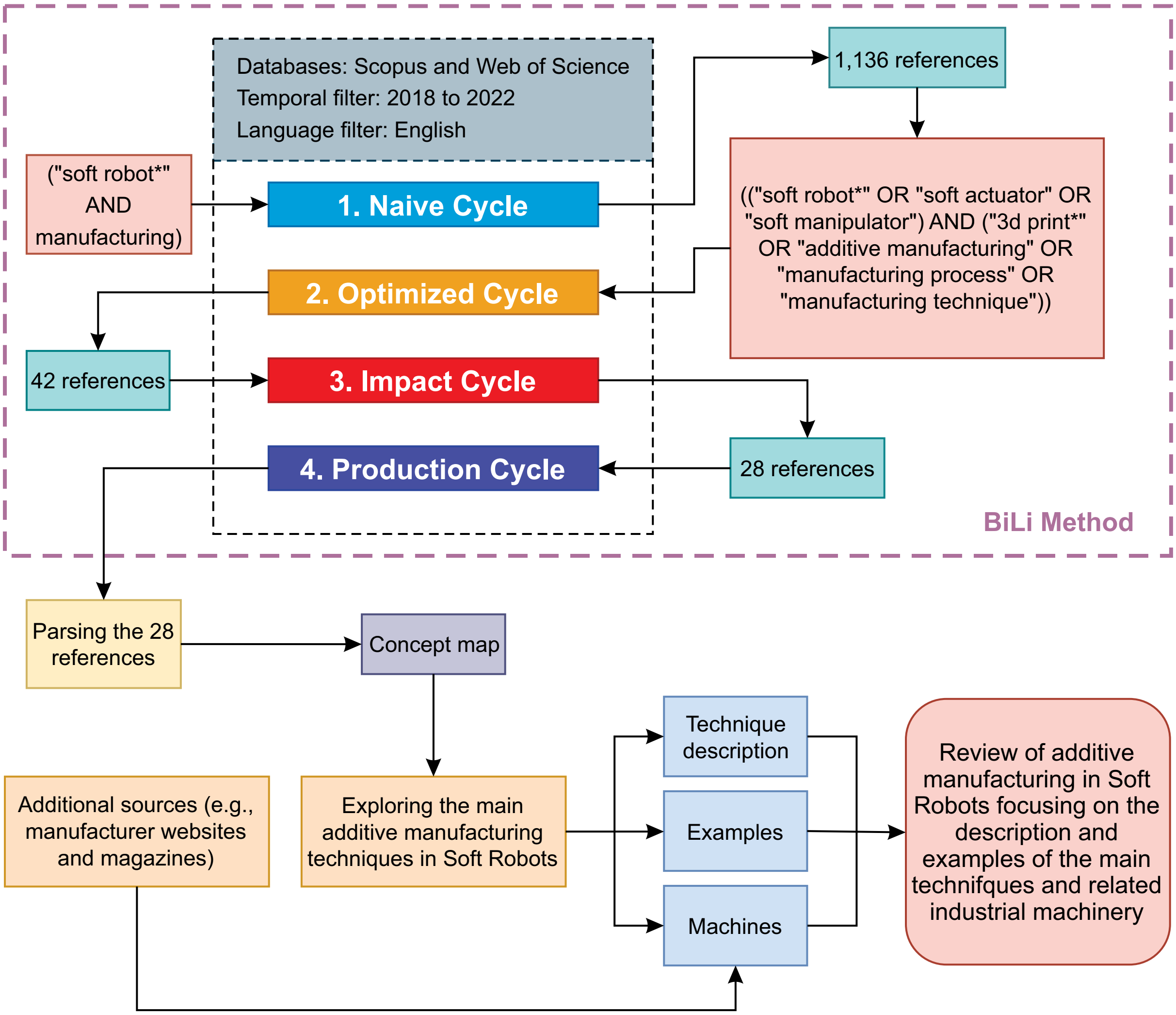
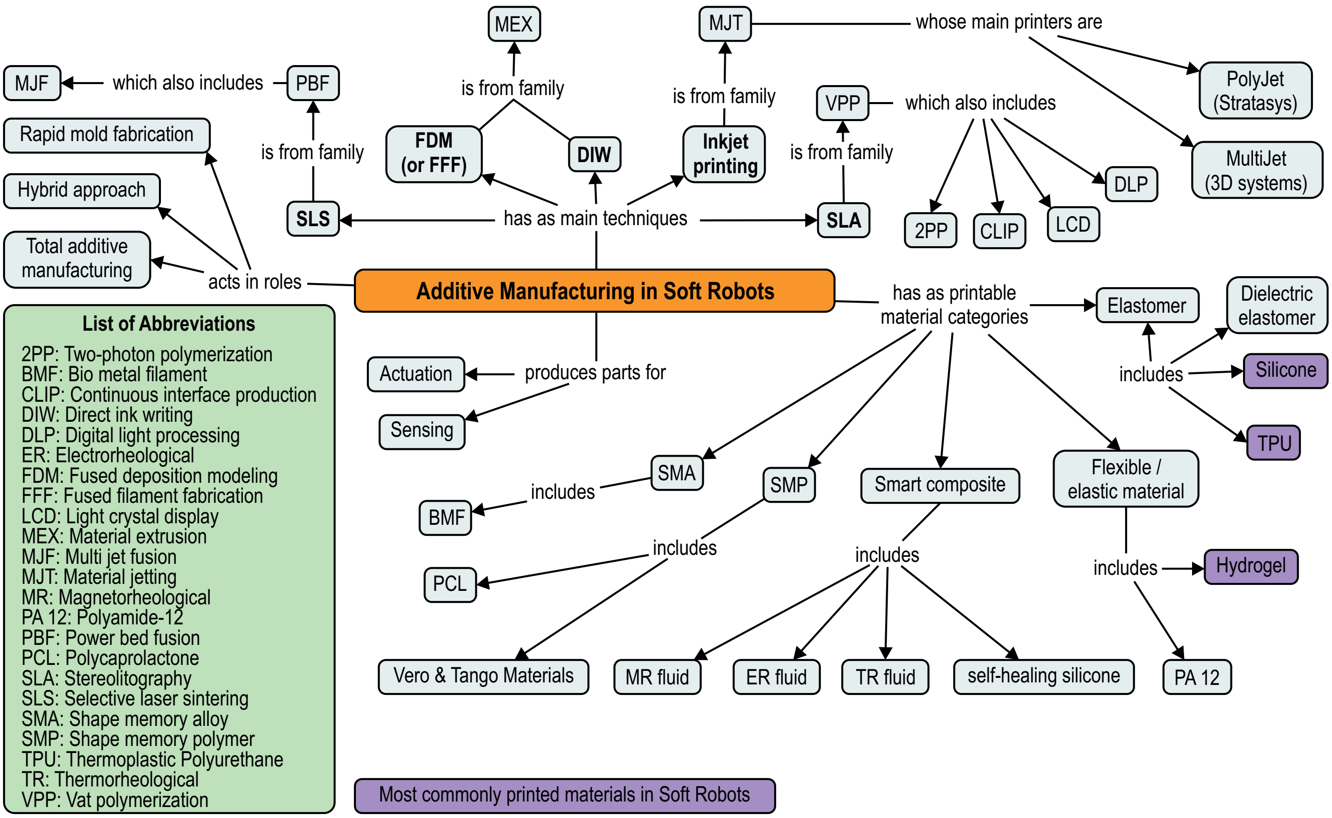


Figure 2. Concept map regarding additive manufacturing in soft robots



FDM

Fused deposition modeling (FDM) is one of the most common AM processes, with wide adoption, especially in research centers. The material – usually thermoplastic filament – is extruded layer by layer, being printed continuously. Materials often used in FDM machines are polycarbonate (PC), polylactic acid (PLA), nylon, and acrylonitrile butadiene styrene (ABS). This technology allows printing a wide range of geometries, and the principal advantages of this method are linked to its low cost and ease of use. However, FDM printers usually present low resolution, poor surface quality, and long printing times, depending on the material's filaments [4].

The literature reports some cases where FDM was used to print soft robots, like a soft-legged robot presented in Xia and colleagues [7]. It comprises a soft body with motor modules inside, soft legs, and electronics, each leg being independently actuated by a servo motor. The soft body and legs were printed using a desktop 3D printer (Troodon CoreXY printer, VIVEDINO) and a flexible thermoplastic polyurethane (TPU) filament.

Soft pneumatic actuators with complex geometry were printed in Yap and colleagues [8] using FDM technology and a commercially available filament, NinjaFlex TPU. Through a low-cost 3D printer (Geeetech Prusa Pro C), the authors printed four soft actuators and built a soft gripper that could grasp objects up to 5 kg. Similarly, in Curkovic and Cubric [9], the authors utilized a Prusa FDM printer with the same material to print soft fingers to form an anthropomorphic hand.

DIW

Direct ink writing (DIW) is an extrusion-based printing process where the ink is extruded, layer by layer, through a nozzle under controlled flow. Some additional steps may be required to solidify the printed object completely. DIW is one of the most flexible 3D technologies [10], and with simple adaptations, it is possible to have multi-material parts, switches, or mixing inks. The possibility of using conductive inks allows DIW 3D printers to create sensitive elements and actuator elements. DIW technique is compatible with many printable materials, including electrical, biological, and structural ones, e.g., colloidal suspension, hydrogel, and thermoset polymers. Besides, it enables the production of tiny patterns with high precision.

DIW technology was utilized to print multi-material pneumatic actuators made from a hybrid resin composed of silicon and epoxy [11]. The printing was conducted on a commercially available 3D printer System 30M, Hyrel INC. In Zhou and colleagues [12], the authors utilized DIW to print soft sensors and pneumatic-actuated artificial muscles. In addition, a multi-material ink composed of silicone and nanosilica (NS) was developed, and results indicate that adding NS increases the silicone ink's viscosity.

In Guan and colleagues [13], a new hybrid magnetorheological material was presented and fabricated using a custom-made printer in a soft gripper by DIW 3D technology. By adjusting the magnetic field, the gripper developed accurate grab and release tasks, indicating that the developed material is feasible for applications in soft robotics. A custom-made 3D DIW printer was also used in [14], where the authors printed a soft pneumatic manipulator made of carbon gel.

SLS

Selective laser sintering (SLS) is a powder bed fusion (PBF) technique applicable to metals and polymers that uses a rastering laser to fuse solid grains of powder in a powder bed [1,5]. Once the irradiation stops, the material cools and fuses. Then, a new powder layer is deposited on the bed, repeated until the part is built [3]. In the process, the non-fused powders act as support material, being reused after fabrication to reduce material consumption [1]. SLS is very similar to multi-jet fusion (MJF), whose principle is also based on powder fusion. The main difference is the heat source. In SLS, a laser is used to scan and sinter across each cross-section, while in MJF, an ink (fusing agent) is dispensed on the powder to absorb infrared light, which fuses the inked areas [15].

The main advantages of SLS are the possibility of material reuse and the achievement of isotropic mechanical proprieties in the printed object. However, among the disadvantages stands out the constraints regarding material compatibility and the need for precise temperature control to maintain an appropriately sized melt pool to fuse the material without distorting it [3,20].

Researchers have used SLS to fabricate soft robots. For instance, in Rost and Schädle [17], a silicone robotic hand was printed with four fingers and twelve degrees of freedom using bellow actuators to perform complex tasks like lifting, rotating, and precisely positioning a ball made of polystyrene. In Roppenecker and colleagues [18], a multi-arm snake-like robot was printed with PA 12 to manipulate instruments at the tip of a flexible endoscope.

Inkjet

Another option for printing soft robots is inkjet, an AM technique that uses several nozzles to jet droplets of different liquid or molten materials on a platform, which become solid by the vitrification process, evaporation, or polymerization. The droplets can also use components sensitive to UV light to solidify the material in a rapid and controlled process that accumulates the material in 2D layers to form high-precision 3D objects directly [3].

In Drotmand and colleagues [19], the materials were combined through selective deposition of different materials to build a pneumatic actuator for a legged robot capable of navigating over unstructured terrain. Using the same printer – Objet500 Connex3 PolyJet –, the authors in Zatopa and colleagues [20] developed a soft robot with integrated fluidic circuitry. Finally, in Shorthouse and colleagues [21], a soft actuator capable of bending bi-directional motions was printed with the Stratasys J735 printer with multiple materials.

SLA

The stereolithography (SLA) technique uses a container with photopolymer resin and a laser or ultraviolet light source to solidify a defined area through polymerization. Then, a layer is printed by moving the laser beams on the material's surface layer by layer to form a complete and unique object [3].

Different light sources and materials can be used to form structures and maintain a high resolution, being a commercially attractive technique for soft robots with microscale characteristics and complex geometry. The materials usually applied for this method are poly(ethylene glycol), diacrylate (PEGDA), acrylic-PEG-collagen mixtures, elastomeric precursor, and Spot-E, Spot-A resins [1]. For instance, one application developed a miniaturized walking biological machine with an actuation module for movement with PEGDA hydrogel and the SLA 250/50 printer from 3D Systems [22]. Another example was the building of Tango Plus elastomer test samples using a Stratasys Objet260 Connex 3D printer [23].

Industrial-Sized Commercial Machinery Models

Among the models of AM machines available on the market, some stand out for their applicability in the industrial environment, productive capacity, printing volume, manufacturing quality, and manufacturer consolidation. Table 1 shows machine models of the techniques mentioned above, which have the potential to constitute an AM facility focused on the manufacture of big soft robots. Models were selected from the literature [21,24], a manufacturer's website [25], and a digital magazine [26,27].

The best option for printing large-volume parts is the Tractus 3D T3500, with a building volume of 1.65 m^3 and a maximum height (z) of more than 2 m. According to Wallin and colleagues [3], the best options in terms of productivity are SLS and SLA, with an approximate deposition rate of 106 mm^3/h, while DIW and SLA are the best regarding resolution, reaching up to 1 µm. These values cannot be generalized to the machines in Table 1, making it necessary to consult the technical datasheet for each equipment.

Conclusion

We showed a compilation of AM techniques aimed at fabricating soft robots – FDM, DIW, SLS,

Table 1. Examples of industrial-sized commercial additive manufacturing machines.

	Printer Model	Building Volume (mm)	Printable Materials
FDM	Tractus 3D T3500	Ø 1000 x 2100	PLA, PETG, ABS, TPU, TPE
	Stratasys F900	914 x 609 x 914	ASA, ABS, PC, Ultem, Nylon
	Roboze 1000	1000 x 1000 x 1000	PLA, ABS, PC, Nylon, Peek, Ultem
DIW	Lynxter S600D	Ø 390 x 600	Silicone (with toolhead LIQ21)
	Delta Tower Fluid MT	Ø 420 x 400	Almost all fluid and pastes
	InnovatiQ LiQ 320	250 x 200 x 150	Silicone
SLS	EOS FORMIGA P 110 Velocis	200 x 250 x 330	Alumide, PA 1101, PA 1102 black, PA 2200, PA 2201, PA 3200 glass filled, PrimeCast 101, PA 2105
	Nexa3D QLS 820	350 x 350 x 400	PA 11, PA 12, PBT, PP, aluminum, glass and fiber-filled
	Sindoh S100	510 x 510 x 500	PA 11, PA 12, TPU, PP
Inkjet	Stratasys Objet500 Connex3	490 x 390 x 200	Resin, ABS
	Stratasys J750	490 x 390 x 200	
	Stratasys J4100	1000 x 800 x 500	
SLA	Stratasys Neo800	800 x 800 x 600	Open resin system*
	3D Systems ProJet 7000 HD	380 x 380 x 250	VisiJet SL Flex, Tough, Clear, Black
	3D Systems ProX 950	1500 x 750 x 550	Thermally resistant plastic, polypropylene, ABS, Accura resin

* Compatible with commercially available 355 nm stereolithography resins.

Inkjet, and SLA – by relevant works in the area, mined by the BiLi method. Finally, we presented a summary containing options of industrial-sized machines with the potential to compose a facility for soft robot manufacturing.

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