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A REVIEW OF SMART STRUCTURES AND ADAPTATION OF 3D PRINTING METHODS FOR FUTURE FASHION APPLICATIONS

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Abstract. The rapid advancement of innovative technological processes necessitates the fashion industry to contemplate novel perspectives it can offer. Additionally, the industry is progressively reducing its reliance on natural monofilaments and transitioning towards synthetic fabrics with new characteristics, employing intricate composites. The emergence of smart materials incorporating microencapsulation, shape-memory materials, and sensors responsive to external stimuli further contributes to this trend. Efforts are being made to incorporate wearable electronics in the form of flexible multifunctional devices. However, the creation of such novel materials/structures and their integration with traditional fibres present numerous challenges, urging the industry to explore new manufacturing methods. This review primarily focuses on actively developing types of passive intelligent structures discovering their properties and advantages in relation to future clothing. Given that progress is achieved through programming and modifying the structures themselves using new materials/composites, prototyping plays a pivotal role as a problem-solving process. It involves searching for new production methods that can rapidly and cost-effectively help achieve desired outcomes. Presently, additive technologies represent one of the most successful and rapidly advancing alternative manufacturing methods. Consequently, they have been widely applied and actively developed in fields such as soft robotics, biomedical devices/sensors/fabrics, flexible wearable electronics, 4D printed structures, and other clothing components and accessories. The applicability of these technologies is illustrated in creating each specific type of smart structure under consideration by briefly describing 3D printing methods and providing examples of their usage. This serves to demonstrate how effectively and qualitatively they enable the prototyping of various multilayered structures and composites. Furthermore, these technologies hold the potential for integrating dissimilar processes, thereby facilitating the development of new smart fabrics with a significantly greater range of variations in the future. Overall, this article aims not only to demonstrate the suitability of additive technologies for smart structures but also to identify technological trends for future research in the fashion industry.

Keywords: 3d printing, smart textile, shape memory, 3d printed fabric, flexible 3d printed textile

Introduction

The term “smart textile” encompasses a broad spectrum of innovative approaches in clothing production, including the novel technologies employed therein. Initially, the development of this field involved synthetic fabrics and diverse coatings for organic fabrics. The subsequent stage saw the emergence of functional fabrics (such as membranes, antibacterial fabrics, radiation protection fabrics, microfibres, etc.) (Júnior et al., 2022). This allowed the fashion industry to significantly improve the quality of clothing in terms of practicality, tactile sensations, and wearability and enhanced the functions of traditional fabrics, such as moisture removal, water resistance, insulation, wind protection, and breathability (Shi et al., 2019).

Currently, the concept of passive smart textiles has gained widespread development, suggesting that the material itself (or its structure) possesses innate responsiveness to external stimuli. For instance, alterations in ambient temperature elicit corresponding modifications in the internal structure of such a smart material. Another facet of passive textile development encompasses the integration of external elements, such as sensors, into clothing. This field has witnessed three generations of advancement: the initial generation entailed sensors attached to the outer layer of clothing, the subsequent generation involved sensors embedded within the fibres, and the last generation entails fibres themselves functioning as sensors (Júnior et al., 2022; Ruckdashel et al., 2022). The emergence and advancement of active smart textiles have been driven by the potential to control and communicate with the elements that could sense/process the wearer/environment state. It is important to acknowledge that the development of this field encompasses not only the materials used but also the internal structural design and production methods. In their turn, these aspects are also intertwined and mutually influential (Rotari, Negara, 2017; Ruckdashel et al., 2021).

One of the major challenges in the research and progress of applying smart textiles lies in the complexity involved in integrating different technologies and components. Numerous unresolved issues persist in relation to multipurpose and multifunctional electronic structures, as well as their intercommunication facilitated by a network of wires, which have to be harmoniously integrated into the process of creating the final fabric (Rotari, Negara, 2017; Júnior et al., 2022). Another challenge pertains to future production and its automation, which necessitates the ability to create miniature multilayer composites/sensors and integrate them into textiles (Razzaq et al., 2022). Various questions regarding future standardisation, which should align with the basic principles of smart textiles, also need to be addressed (Ruckdashel et al., 2022). Moreover, incorporating wearable energy generators, energy storage sources, image fibre devices, and other multifunctional devices into everyday clothing poses difficulties, as conventional electronic devices, wires, and batteries are not easily compatible with conventional norms of fashion (Younes, 2023).

Prototyping methods

One of the most promising methods in modern manufacturing and prototyping is 3D printing, which is already extensively used in constructing structurally complex electronic devices on flexible substrates while also offering customisation and design adaptability (Valentine et al., 2017; Yang et al., 2018; Xu et al., 2017; Hassan et al., 2023). This innovative technology is being actively explored as a future potential solution to the aforementioned challenges associated with fabricating smart structures and sensors (Wu et al., 2022). Specifically, “3D printing” is a collective term for additive manufacturing, a process wherein materials are deposited layer by layer to create a three-dimensional object despite variations in the actual methods employed (Iftekar et al., 2023; Xu et al., 2017). There are key types of 3D printing that are either already in use or hold potential for prototyping and manufacturing smart textile structures (Fig. 1).

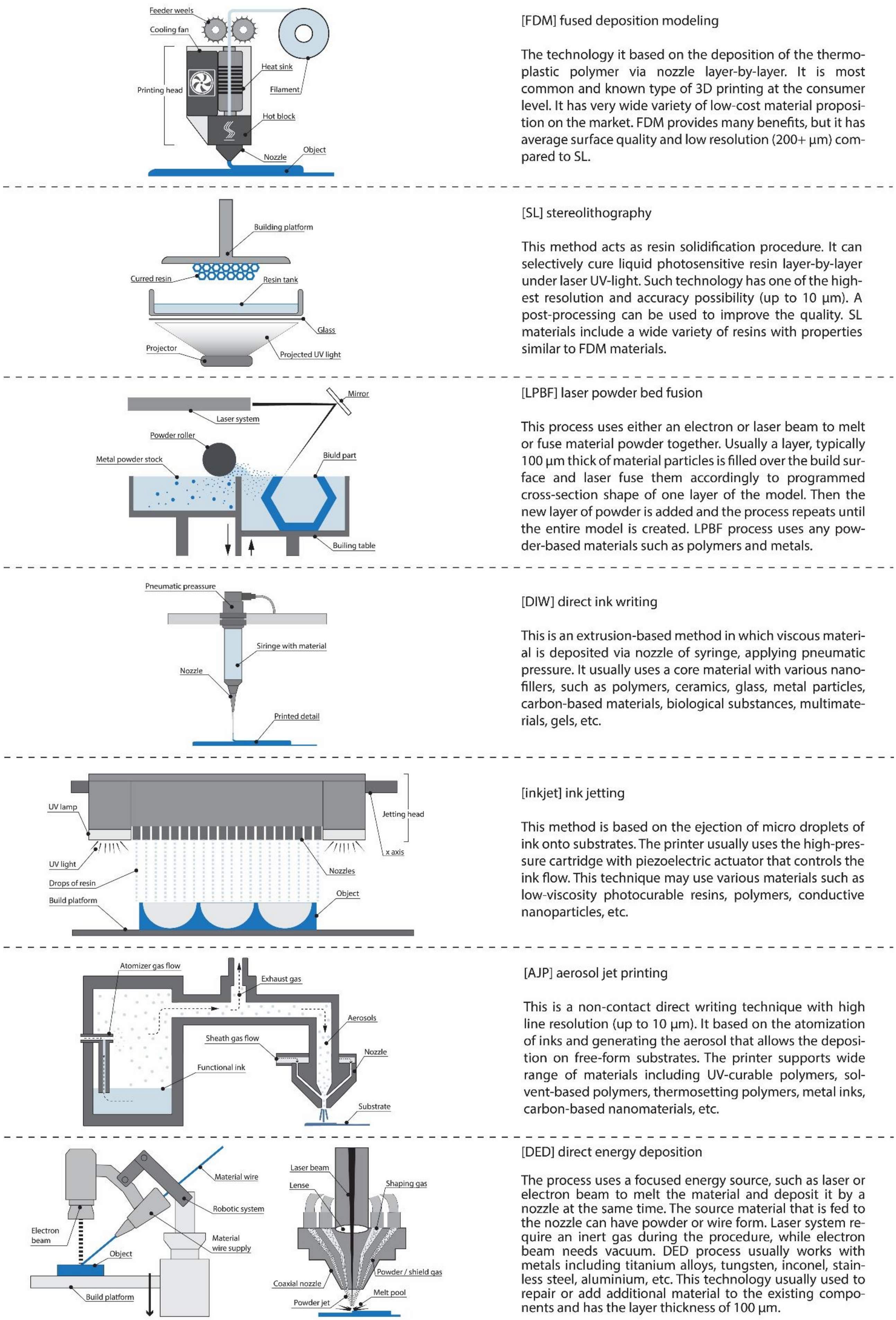
While they are not yet alternatives to the traditional manufacturing methods employed in the textile industry, these techniques possess the capability to address special tasks that are economically and practically inefficient when using conventional methods (Wu et al., 2022). Furthermore, future textile production may probably shift towards additive technologies, aiming to directly and simultaneously prototype synthetic multi-material fabrics and smart structures through a unified mono process. With the introduction of such a production method, significant advancements can be made in integrating electronics into clothing, alongside the development of new technological processes and 3D printers specifically designed to tackle these challenges.

Considering the intrinsic logic of stimuli-responsive smart structures, it is worth noting that their behaviour is directly linked to their programming, as they rely on external stimuli such as temperature, electricity, light, mechanical forces, and chemical effects. In this context, 3D printing enables researchers to extensively experiment with printing settings to achieve desired target values and parameters under specific conditions. The overall systemic approach also entails a significant focus on the materials used in these processes, as their properties influence both the achieved effects and the production methods themselves.

Another noteworthy area of research pertains to 3d-microstructures, which play a pivotal role in achieving self-cleaning/self-healing effects, for instance. Additive technologies prove highly effective in prototyping such microstructures, particularly those with closed pores. Furthermore, significant progress has been achieved in using 3D printing for sensor encapsulation and direct printing of conductors, such as conducting and optical fibres, on textile fibres or other flexible surfaces (Ji et al., 2021; Shi et al., 2019). The aforementioned passive intelligent structures will be further explored in subsequent sections while briefly analysing the existing possibilities of additive technologies employed in their prototyping.

Shape Memory Materials (SMM)

One example of a stimuli-responsive material is Shape Memory Materials (SMMs), which can be programmed to a temporarily programmed shape and autonomously recover to the original shape when exposed to external stimuli, demonstrating the so-called Shape Memory Effect (SME). The primary activation mechanisms include thermal, chemical, mechanical, electrical, or radiation methods (Wu et al., 2013; Ji et al., 2021). There are several groups of such materials, including shape-memory alloys (SMA), shape-memory polymers (SMP), and shape-memory ceramics (SMC). They are commonly embedded in composite fabrics, contributing to intelligent functions such as wettability, breathability, temperature regulation, and protection from the external environment, particularly in the creation of shock-absorbing fabrics. Additionally, these materials enable the realisation of aesthetically pleasing crease retention fabrics or form-fitting fabrics with pressure adaptation (in contrast to spandex, which applies pressure when the size of the object changes).



[FDM] fused deposition modeling

The technology it based on the deposition of the thermoplastic polymer via nozzle layer-by-layer. It is most common and known type of 3D printing at the consumer level. It has very wide variety of low-cost material proposition on the market. FDM provides many benefits, but it has average surface quality and low resolution (200+ µm) compared to SL.

[SL] stereolithography

This method acts as resin solidification procedure. It can selectively cure liquid photosensitive resin layer-by-layer under laser UV-light. Such technology has one of the highest resolution and accuracy possibility (up to 10 µm). A post-processing can be used to improve the quality. SL materials include a wide variety of resins with properties similar to FDM materials.

[LPBF] laser powder bed fusion

This process uses either an electron or laser beam to melt or fuse material powder together. Usually a layer, typically 100 µm thick of material particles is filled over the build surface and laser fuse them accordingly to programmed cross-section shape of one layer of the model. Then the new layer of powder is added and the process repeats until the entire model is created. LPBF process uses any powder-based materials such as polymers and metals.

[DIW] direct ink writing

This is an extrusion-based method in which viscous material is deposited via nozzle of syringe, applying pneumatic pressure. It usually uses a core material with various nanofillers, such as polymers, ceramics, glass, metal particles, carbon-based materials, biological substances, multimaterials, gels, etc.

[inkjet] ink jetting

This method is based on the ejection of micro droplets of ink onto substrates. The printer usually uses the high-pressure cartridge with piezoelectric actuator that controls the ink flow. This technique may use various materials such as low-viscosity photocurable resins, polymers, conductive nanoparticles, etc.

[AJP] aerosol jet printing

This is a non-contact direct writing technique with high line resolution (up to 10 µm). It based on the atomization of inks and generating the aerosol that allows the deposition on free-form substrates. The printer supports wide range of materials including UV-curable polymers, solvent-based polymers, thermosetting polymers, metal inks, carbon-based nanomaterials, etc.

[DED] direct energy deposition

The process uses a focused energy source, such as laser or electron beam to melt the material and deposit it by a nozzle at the same time. The source material that is fed to the nozzle can have powder or wire form. Laser system require an inert gas during the procedure, while electron beam needs vacuum. DED process usually works with metals including titanium alloys, tungsten, inconel, stainless steel, aluminium, etc. This technology usually used to repair or add additional material to the existing components and has the layer thickness of 100 µm.

Fig. 1. 3D Printing methods. Source: author (2024)

Other significant applications of SMM include wound monitoring, intelligent drug release control, and energy storage in smart textiles (Gök et al., 2015; Chakraborty et al., 2017; Shi et al., 2019; Júnior et al., 2022; Çelikel, 2020).

Among the types of SMMs, SMPs are extensively researched and have multifaceted applications in smart textiles. The advantages of SMPs over other SMMs include:
- high elasticity (up to 800 per cent stretchability);
- compatibility with the textile's softness;
- low-temperature requirements for activating SME;
- affordability both in terms of materials and production;
- diverse types of SMPs that can form composites with desired properties and be applied to textile surfaces;
- recyclability.

Integrating SMPs into conventional fabrics can be achieved through various methods, including lamination, coating, impregnation, and weaving (Thakur, 2017). In addition to these traditional approaches, a method called 4D printing is currently under active development, which involves 3D printing SMP materials that can be altered when exposed to external stimuli (Ding et al., 2019; Mehrpouya et al., 2021; Razzaq et al., 2022). The advantage of this manufacturing method lies in its relatively simple ability to rapidly, efficiently, and cost-effectively create different types of films, composites, and other 3D structures for rapid prototyping (Razzaq et al., 2022; Mehrpouya et al., 2021; Spiegel et al., 2022). 3D-printed SMP structures find extensive application in various fields, such as biomedicine, sportswear, specialised clothing, robotics, and sensors (Biswas et al., 2021; Li, 2023; Bataglini et al., 2021). The primary printing methods suitable for SMPs include (FDM), (DIW), (SL), and (AJP) (Mehrpouya et al., 2021; Ji et al., 2021; Xu et al., 2017; Mondal, Tripathy, 2021; Razzaq et al., 2022). The main materials used comprise Polylactic Acid (PLA), Thermoplastic Polyurethane (TPU), Polycaprolactone (PCL), Ethylene Vinyl Acetate (EVA), Polyethylene Terephthalate (PET), Polytetrafluoroethylene (PTFE), hydrogels, and other SMP composites (Ameen et al., 2023; Razzaq et al., 2022). These manufacturing methods are unrivalled in terms of cost, quality, and speed, particularly when it comes to models with complex architecture or multi-component systems that combine polymers (SMPs) with metals (SMA) to achieve new functions or enhance thermo-mechanical properties (Razzaq et al., 2022; Ameen et al., 2023; Šproch et al., 2020; Spiegel et al., 2022).

SMA themselves also have unique properties:
- the shape memory effect, unlike SMPs, has a short activation time and high stress;
- super elasticity (SE);
- lightweight and good mechanical properties;
- biocompatibility;
- corrosion resistance and wear resistance;
- lifelong service.

Nitinol (Ni-Ti) stands as the most prevalent material example, characterised by varying properties of shape memory effect and super elasticity depending on the Ni-Ti ratio (Barik, Rao, 2019). However, the application of SMA types and their manufacturing processes, such as (DED) or (LPBF) (Wu et al., 2022; Milosevic et al., 2020), incur higher costs. Anyway, the distinctive properties of Nitinol do not have analogues in other applications. The medical sector actively employs SMA technology for additive manufacturing to create muscles, stents, and smart capsules. The uniqueness of this technology is exemplified in the implant capsule, which contains microcapsules of medication. When the body temperature increases, as in the case of inflammation, Nitinol undergoes a shape change, causing the pores in the implants to open, thereby releasing microcapsules containing medication to suppress infection. Once the inflammation subsides and the temperature decreases, the SMA structure of the capsule returns to its original shape, thereby blocking the release of medication and enabling precise dosage control (Farber et al., 2020; Dulal et al., 2023). The creation of such intricate, porous structures without additive manufacturing would be immensely challenging, considering time, cost, and other constraints, not to mention basic feasibility studies. Considering the active exploration of SMA in smart textiles (Razzaq et al., 2022; Shin et al., 2023), it can be assumed that their combined use with SMP structures through 4D printing offers various prospects for future inventors to test and create prototypes.

Smart Electromagnetic Structures (SEMS)

The electrical nature of the human body plays a vital role in muscle contraction and the transmission of electrical impulses through the nervous system for the overall control of the organism. This natural phenomenon has led to the emergence of various methods of treatment based on electrostimulation, artificial muscle activation, and programmed regulation of different systems with tactile feedback (Milosevic et al., 2020; Xu et al., 2021; Kim, Paik, 2021). Electroresponsive SMP materials can interact with the human body through smart textiles that respond to electromagnetic fields. However, these materials differ from slow shape-memory alloy (SMA) structures in terms of their responsiveness at high frequencies, making them analogous to our nervous system (Trivedi et al., 2008). SEMS, which primarily emerge in robotics, bionic structures, and biomedicine (Panda et al., 2023; Trivedi et al., 2008; Kim, Paik, 2021), operate on diverse mechanisms for transforming electrical energy into mechanical energy, resulting in compression, tension, expansion, twisting, or bending (Ji et al., 2021).

SEMS structures are of two types: dielectric elastomer actuators (DEAs) and electrically conductive hydrogels (EAHs). The conventional fabrication methods for these nanofiber structures involve coating and integrating them into traditional fibres using interweaving techniques (Duan et al., 2021; Wang et al., 2023). Additive manufacturing methods are also used to create similar composite structures and coatings. Key prototyping solutions in these cases include testing methods like (DIW), (FDM), (SL), Inkjet printing, and (AJP) for printing microstructures (Ji et al., 2021; Chortos et al., 2020; Li et al., 2020; Huang et al., 2024; Khalid et al., 2024; Wang et al., 2020). (DIW), often combined with (FDM), is a primary prototyping method for creating artificial muscles and soft actuators (Ji et al., 2021; Kruger et al., 2023; Chortos et al., 2020; Tang et al., 2023). DEA structures are typically controlled through conductive materials, necessitating their connection. These structures consist of elastomer films coated on both sides with electrodes, allowing the structure to assume specific positions with minimal energy consumption and high elastic energy density. These structures do not generate a magnetic field, operate silently, and possess microscopic dimensions. The future of smart textiles heavily relies on DEA structures, as they provide haptic feedback (Chen et al., 2021; Wang et al., 2022; Grellmann et al., 2021), mimicking human skin receptors. In textile developments, DEA is also employed to acquire new capabilities for controlling air permeability and thermoregulation, applying 3D printed structures as actuators (Chortos et al., 2020; Ji, Luan et al., 2021; Xiang et al., 2019).

The most significant challenge concerning future smart clothing is the power supply, and the use of conventional lithium batteries poses several difficulties, prompting the need for alternative energy storage and generation methods. Extensive research is being conducted in various directions, emphasising flexibility, miniaturisation, integration into textiles, hypoallergenicity, and reliability during active use. Hydrogels (Zhang et al., 2019; Li et al., 2020; Chen et al., 2021) play a crucial role in this research domain, as they combine a hydrophilic matrix with various fillers. Additive manufacturing technologies enable experiments with conducting materials like metal powders, conductive polymers, or carbon-based materials and the 3D printing (testing) of samples with different materials. These materials hold promise in creating microscopic energy sources such as micro batteries or supercapacitors (Duan et al., 2021; Zhang et al., 2019), which can be integrated into smart textiles. The internal structure of these polymer composites has the ability to swell and undergo reversible changes under the influence of electromagnetic fields or light, facilitating active fluid-ion exchange for energy generation. These hydrogels can function under bending, stretching, twisting, and systems for delivering various chemical compounds, which is an essential requirement for practical use in smart textiles (Ji et al., 2021; Duan et al., 2021; Grellmann et al., 2021).

The academic sphere views the development of microgenerators of energy as highly promising. These generators can convert thermal and chemical energy from the human body or its kinetic activity (Ying et al., 2023). Notable advancements in this field include triboelectric nanogenerators (TENG), thermoelectric elements (TEG), fuel cells (BFC, HEG), piezoelectric generators (PENG), and flexible solar elements, all serving as external sources of energy generation (Shi et al., 2019; Júnior et al., 2022; Ying et al., 2023). TENG stands out as the most promising technology of the 21st century owing to its simplicity, cost-effectiveness, lightweight nature, wide range of applications, and environmentally friendly characteristics (Shi et al., 2021; Qiao et al., 2018; Tong et al., 2020). Considering that a person in a passive state generates an average of 100W/h, the use of TENG and TEG is actively being explored as innovative means of energy generation in the future (Ying et al., 2023; Ning et al., 2023). The principle underlying this technology is straightforward: two different materials acquire electric charges upon physical contact. The increase in contact area plays a crucial role, and clothing, particularly when technologically manipulated to create necessary micro/ nanostructures, aligns with this criterion. 3D printing, as a manufacturing method, allows for cost-effective and rapid experimentation with different forms and ideas. Hence, it is not surprising that the flexible 3D-printed miniature structure of a TENG generator is already being prototyped using methods like digital light processing (DLP), (FDM), (DIW), and (AJP) (Qiao et al., 2018; Mahmud et al., 2021; Chiappone et al., 2023).

TEG represents another relevant method of energy generation, primarily considering that humans constantly produce heat, which can potentially be converted into electricity through skin contact. Ongoing research on self-healing structures has facilitated the creation of flexible TEGs (using Sb2Te2-Te film and Ag electrodes) through 3D printing methods like (AJP), (screen printing), and (inkjet) printing (Hong et al., 2023; Ruckdashel et al., 2022; Ying et al., 2023). These TEGs possess the ability to operate at body temperature.

While there are well-established alternative methods of energy generation, their integration into smart textiles was challenging until the advent of advanced materials. This situation has changed drastically with the development of flexible solar cells and films based on Perovskite Material (PSC) (Tabassum et al., 2022), a promising technology that provides lightweight properties of solar cells, ease of processing, flexibility, and the ability to encapsulate such solar cell films into smart clothing. Moreover, PSC can be easily manufactured using 3D printing methods like (inkjet), (FDM), (AJP), (DIW), and electrohydrodynamic printing (EHDP), which are actively being tested as primary production methods (Hunde, Woldeyohannes, 2023; Weiss, Sonsalla, 2022).

To summarise, additive technologies offer a diverse and unique opportunity for prototyping complex multi-component systems used in smart textiles, known as SEMS.

Self-Cleaning

The phenomenon of the natural self-cleaning effect of lotus leaves, also known as the “lotus effect,” has paved the way for the development of materials with a similar effect, also observed in the wings of cicadas and dragonflies as well. It has been extensively studied and attributed primarily to the unique microstructure and roughness of the surface of the leaf. The distinctive characteristics minimise the contact area between the surface and dirty water, allowing water to effectively wash away dirt by rolling off the leaves. Another approach to achieving the same effect involves the use of extremely slippery surfaces that prevent the adherence of any substances and are also resistant to fogging and icing (Atwah, Khan, 2023; Zhou et al., 2023). This breakthrough has empowered researchers to modify hydrophobic coatings for textiles. The adoption of self-cleaning materials not only ensures a clean surface but also prolongs their lifespan and strengthens their durability, as it reduces the need for resources that would otherwise be expended on cleaning. An additional “byproduct” of superhydrophobicity is the eradication of unpleasant odours and the acquisition of antibacterial properties (Cheung, Li, 2018; Zhou et al., 2023).

The primary technological solutions for producing such fabrics entail the application of specialised chemical solutions to the surface of the material or the implementation of specialised films with microstructures (Cheung, Li, 2018). The hydrophilic properties of organic materials like wool and cotton can be transformed into superhydrophobicity by augmenting the roughness of their surface, thereby decreasing the adhesion of pollutants and facilitating their removal through photolytic methods (Atwah, Khan, 2023; Cheung, Li, 2018; Zhou et al., 2023). The dip coating method is usually employed for simple fibre structures (Atwah, Khan, 2023), whereas, for multilayered and voluminous surfaces or composites, 3D printing could be the preferred technique. Currently, researchers are investigating and testing methods such as (FDM), (DIW), and (inkjet), as well as more precise (AJP) and (SL), which offer enhanced roughness owing to their micron-level resolution (Liu et al., 2023; Atwah et al., 2022; Barraza et al., 2022). Conventional chemical films and solutions used for hydrophobic coatings merely create a nanolayer that demonstrates limited resistance to wear in cyclic tests, whereas 3D-printed composites allow for the creation of layers of any desired thickness. This feat is challenging to accomplish with other approaches. Furthermore, it is noteworthy that expensive chemical processes and drying are not required in this case (Chan et al., 2023; Atwah et al., 2022).

The use of 3D printing for superhydrophobic surfaces holds significant potential and requires further attention from researchers. It is particularly relevant for the future of smart textiles, where such surfaces or protective films could address challenges related to cleaning electronic textiles that incorporate embedded power sources and energy generators, optimising energy transport with minimal losses (Wen et al., 2020; Getaneh et al., 2023; Zhang et al., 2021).

Smart-Sensing

The diagnostic and analysis systems play a crucial role in human vital activity. The human sensory system consists of various types of biosensors because a human body cannot function without them. It pertains to the precise evaluation of programmed bodily functions or the generation of appropriate responses to external stimuli or internal malfunctions. Today's advanced neural networks are a highly simplified analogue of the bio-electronic system. Still, they boast the unique ability of instant digital transmission, storage, and duplication of vast data arrays, which are not inherent in the human biological system (Goel et al., 2023). Such systems can serve as an equivalent to the sensory system, simultaneously gathering data from both the body and the environment using smart textile sensors (Cleary et al., 2023; Heukenfeld et al., 2018; Xu et al., 2017; Jiang et al., 2023; Liu et al., 2022). Research is ongoing to develop flexible sensors for various parameters such as motion, temperature, pressure, light, acceleration, chemical element concentration, humidity, voltage, heart rate, etc. (Heukenfeld et al., 2018; Xu et al., 2017).

The microelectronics industry has significant experience in sensor research and development to meet its needs. The challenge lies in the complex and costly manufacturing of miniaturised and encapsulated sensors, particularly in the fully automated integration of fibre-optic devices into textile products. Promising attempts, such as an automated weaving process for the textile electronic system (Lee et al., 2023) and inflight fibre printing (iFP) (Wang et al., 2020), are being made in this direction.

The primary manufacturing techniques employed in traditional electronics involve intricate and multi-step procedures, such as lithography, film deposition, etching, photolithography, subtractive nanomanufacturing, polishing, alloying, metallisation, etc. (Corzo et al., 2020; Remaggi et al., 2022; Han et al., 2023). However, these methods often prove unsuitable for producing flexible electronics due to factors such as high processing temperatures, instability in substrate size, the need for precise processing and alignment, delamination issues, and complex polishing requirements (Corzo et al., 2020; Han et al., 2023). Consequently, researchers have sought alternative solutions, leading to the emergence of methods based on direct pattern transfer, ink printing, and stencil printing (Corzo et al., 2020; Valentine et al., 2017; Han et al., 2023). As a result, additive technologies have gained significant momentum in developing flexible tiny components due to their efficiency, quality, speed, reliability, and commercial advantages in prototyping and adaptability to diverse production processes. These inherent advantages undoubtedly position this technology as highly coveted within Industry 4.0 (Jandyal et al., 2022; Chandrasekaran et al., 2022).

Furthermore, with a focus on sustainable development, 3D printing holds immense appeal not only for its potential for waste-free production but also for its ability to concurrently combine multiple materials and composites (such as metals, ceramics, polymers, organics, and semiconductors) in a single process (Jandyal et al., 2022; Xu et al., 2017), thereby facilitating the design and realisation of complex 3D objects with desired properties, including printing on specific substrates (Yang et al., 2018). Presently, techniques such as (FDM), (DIW), (AJP), and (inkjet) are widely employed for 3D printing various types of flexible sensors, such as environmental sensors [52: Tbl2], fibre-optic sensors (iFP) (Wang et al., 2020), biosensors [49: Tbl1] (for non-invasive measurements), and artificial electronic skin sensors (Ji et al., 2021; Hassan et al., 2023; Gao et al., 2022) that can possess self-healing properties. Moreover, efforts are underway to develop hybrid 3D printing methods for smart textiles, which combine 3D printing processes (DIW) with electronic assembly (pick-and-place method) and leveraging technologies borrowed from the microelectronics industry to create printable electronics on flexible substrates and organic electronics (Valentine et al., 2017; Han et al., 2023; Yang et al., 2018). All in all, it is imperative to reiterate that the future of smart textiles relies heavily on identifying suitable, cost-effective, and dependable methods for integrating sensors into fabric structures. Additionally, the prospect of a hybrid manufacturing approach for new fabrics, where the sensors themselves are integrated inside 3D-printed textiles, holds promise in revolutionising the textile industry.

Perspective

In conclusion, it is worth noting that smart textiles represent the future stage of the fashion industry due to the numerous advantages they offer. As observed, the development of passive smart materials and structures that respond to external stimuli can significantly enhance the comfort level of clothing. The widespread adoption of such innovations depends on how well they can be adapted to existing textile production processes, although there are several challenges in this regard.

It is evident that when it is possible to complement or modify new/existing processes without changing the core production, innovative materials or coatings can be quickly integrated into the mass market. Conversely, when a new structure requires a completely distinct manufacturing approach and cannot be integrated into the existing textile process, significant problems arise. These issues demand intricate and costly modifications due to persistent attempts to use fabric as a substrate for incorporating/attaching sensors, for example. From our perspective, such an approach will require extraordinary endeavours in the future due to the unique attributes of each structure and the corresponding need for technological innovations. Furthermore, all these processes face a major obstacle: the inability to alter the fundamental technology governing fibre production that serves as the bedrock of textiles.

This review specifically highlighted and investigated various additive manufacturing methods as prospective means for producing/integrating smart structures, including those based on textiles. It has been demonstrated that such technologies not only have the ability to prototype diverse structures but also combine different technological processes, thereby bridging gaps between textiles and microelectronics. From our standpoint, it is apparent that there exists a general lack of appreciation within the field dedicated to developing smart textiles regarding 3D printing, primarily due to preconceived notions about its incapacity to replicate textile fibres. However, recent advancements have challenged this notion and eliminated doubts about being able to produce 3D-printed textiles and smart structures (including microelectronics) in a singular process.

Acknowledging the obvious fact that 3D printing technologies are primarily used for design and prototyping purposes, this article emphasises their versatility and practicality in addressing various challenges related to smart structures. It is important to reiterate that the future textile industry primarily requires a deep understanding of alternative production methods. Without such comprehension, it is complicated to envision the development of new manufacturing methods for smart textiles based on additive technologies, as well as potential investments in forthcoming research programmes in this domain.

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IŠMANIŲJŲ STRUKTŪRŲ APŽVALGA IR 3D SPAUSDINIMO METODŲ PRITAIKYMAS ATEITIES MADAI

Santrauka

Sparti inovatyvių technologijų plėtra skatina mados industriją galvoti apie naujas perspektyvas. Pastebima, kad pramonininkai palaipsniui mažina savo priklausomybę nuo natūralių monofilamentų ir naudodami sudėtingus kompozitus pereina prie sintetinių audinių, turinčių naujų savybių. Prie šios tendencijos dar labiau prisideda išmaniųjų medžiagų, apimančių mikrokapsuliaciją, formos atminties medžiagas ir į išorinius dirgiklius reaguojančius jutiklius, atsiradimas. Stengiamasi įtraukti nešiojamą elektroniką lanksčių daugiafunkcinių prietaisų pavidalu. Vis dėlto tokių naujų medžiagų ir struktūrų kūrimas ir jų integravimas į tradicinius pluoštus kelia daug iššūkių, todėl pramonininkai raginam ieškoti naujų gamybos metodų. Šioje apžvalgoje daugiausia dėmesio skiriama aktyviam pasyvių intelektualių struktūrų tipų kūrimui, jų savybių ir privalumų, susijusių su būsimais drabužiais, atradimui. Atsižvelgiant į tai, kad jų plėtra vyksta naujų medžiagų ir jų kompozitinių struktūrų programavimo ir modifikavimo keliu, pagrindinį vaidmenį sprendžiant problemas atlieka prototipų kūrimas. Tai apima naujų gamybos metodų, kuriais galima greitai ir ekonomiškai pasiekti norimų rezultatų, paiešką. Pavyzdžiui, šiuo metu vienas sėkmingiausių ir sparčiausiai tobulėjančių alternatyvių gamybos metodų yra adityviosios technologijos. Jos plačiai naudojamos ir aktyviai plėtojamos tokiose srityse kaip minkštoji robotika, biomedicinos prietaisai / jutikliai / audiniai, nešiojama lanksti elektronika, 4D spausdintos konstrukcijos, taip pat kiti drabužių komponentai ir aksesuarai. Apžvalgoje aptariamas šių technologijų pritaikomumas kuriant kiekvieną konkretų nagrinėjamos išmaniosios struktūros tipą, trumpai apibūdindami 3D spausdinimo metodai ir pateikdami jų naudojimo pavyzdžiai. Atskleidžiama, kaip efektyviai ir kokybiškai jos įgalina įvairių daugiasluoksnių struktūrų ir kompozitų prototipų kūrimą. Be to, šios technologijos turi potencialo integruoti skirtingus procesus ir taip palengvinti naujų išmaniųjų audinių, kurių variacijų spektras ateityje bus gerokai įvairesnis, kūrimą. Apibendrinant, šiuo straipsniu siekiama ne tik pademonstruoti adityviųjų technologijų tinkamumą išmaniosioms struktūroms, bet ir nustatyti technologines tendencijas būsimiems mados pramonės tyrimams.

Reikšminiai žodžiai: 3D spauda, išmanioji tekstilė, formą įsimenančios medžiagos, 3D spausdinta medžiaga, lanksti 3D spausdinta tekstilė

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