Miniaturized soft robotics: recent advances and futures opportunities

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Abstract

Purpose of review: This review proposes an analysis of the scientific challenges of Soft Miniaturized Robots, providing a map of the recent works in this emerging field.
Recent findings: The advent of precision 3D microprinting technologies enabling to build microstructures and micro-actuators based on soft polymers has open a way to the development of soft miniaturized robotics in several fields: (i) Some swimming soft microrobots actuated with an external field enable to explore high small channel for in-vitro or in vivo applications; (ii) Miniaturized soft robot based on artificial muscles find applications in in-vivo exploration or in dexterous micromanipulation.
Summary: Placing at the crossroads of small-scale robotics and soft robotics, miniaturised soft robots has his own scientific paradigm, that we describe in this article. It requires to develop methods and technologies to design, actuate and fabricate this new type of miniature robots. The intrinsic non-linear behaviour of these robots requires advanced methods to model and control them.

Keywords: soft robotics, miniaturized robotics, microrobotics, compliance, compliant actuators.

Introduction

Soft miniaturized robots including robot from millimeter scale to nanoscale present immense promise for multiple fields to ensure safe and gentle interactions with micro-nano scale or miniaturized scale environments [1]. For example, soft miniature robots enable to manipulate highly fragile micro-objects in a safe way taking advantage on the robot compliance [2].

Due to the complex physics that governs the microworld [3] and limitation in terms of fabrication [4, 5], the design and control of robots acting in micro-nanoscales require specific methods and most of the concept in macroscale robots cannot be directly applied in the smaller scales. The current miniature robotics approaches are often bio-inspired and tend to address some challenges common to robotics as grasping, positioning, and locomotion [6, 7]. Miniature robotics also faces particular challenges rely on the envisioned applications and their technical requirements. Particularly, nanomanipulation in vacuum, lab-on-chip for cell sorting and characterization, and intracorporeal robots in confined spaces for computer assisted interventions open new challenges in which the robot compliance and dexterity could enable to improve the performances.

Contrary to robots operated by traditional motors with rigid links, soft robots have the ability to absorb energy allowing them gentle manipulation and safe interaction with the environment similarly to biological muscles. To handle fragile and complex micro-objects, conformable and configurable robots with accurate positioning and soft end effector are required to advance industrial and medical applications. Researchers have been developing miniaturized soft robots with impressive performances through proof-of-concepts [1, 8–11] covering gripping, multi-modal locomotion, and positioning.

Miniaturized soft robots is defined by the intersection of the definition of both miniaturized robots acting in micro-nanoscale and soft robots having compliance [1, 12]. Miniaturized soft robotics is considered as nm-scale to mm-scale robots covering manipulator, gripper and mobile robots for various applications. During the last decade, new concepts/paradigms and disruptive advances in this field have conducted to a flood of impressive results reported and discussed in this review. In the following, this review paper is organised in 4 sections including section 1 on actuation and design of soft miniaturized robots, section 2 on robot's fabrication, section 3 on modeling and control, and finally section 4.3 concludes and discusses some future directions.

1 Actuation and Design

1.1 Soft Miniaturized Robots Actuation

Selecting a soft robot actuator depends on multiple requirements such as the number of degrees of freedom (DoF), environment (e.g. air, liquid, liquid interface), size, manipulated object properties, etc. Thus far, various actuation techniques have been studied for small-scale soft robots and can be classified to two types: (i) remotely actuation and (ii) with contact actuation, in which several actuation principles can be used. Figure 1 summarizes some examples of soft actuators classified by actuation type.

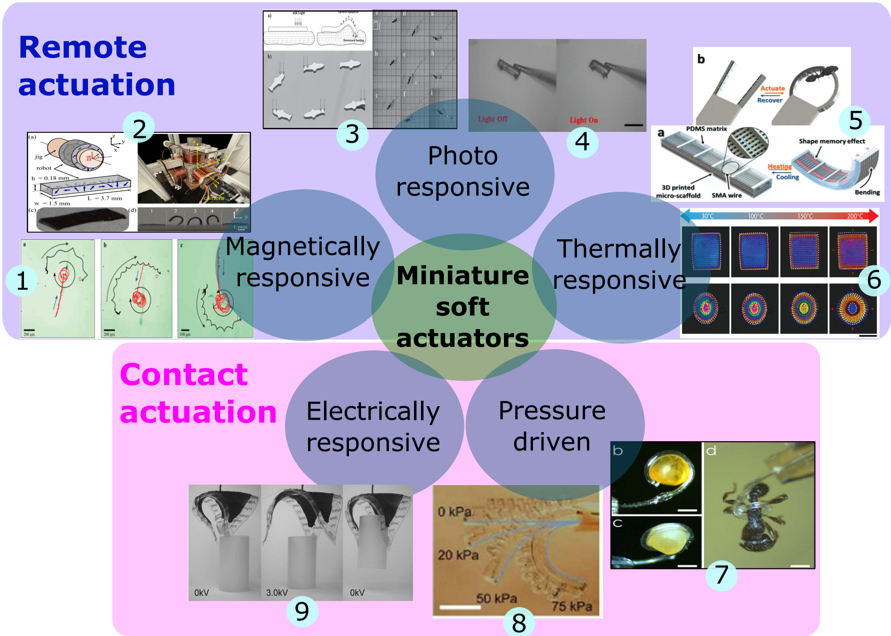

Fig. 1 Types of soft micro-actuators and examples: (1) Magnetic dipole microrobot orbiting a sprocket-like trajectory due to a periodic and asymmetric flow-field caused by the two tails (© [2020] IEEE. Reprinted, with permission, from [13]). (2) Soft magnetic robot controlled with 6 electromagnetic coils (© [2020] RSS fundation. Reprinted, with permission, from [14]) (3) Artificial soft microfish driven by nIR light irradiation (© [2014] John Wiley and Sons. Reprinted, with permission, from [15]). (4) Micro soft walker robot actuated by laser beam (scale bar: 50μm) (© [2015] John Wiley and Sons. Reprinted, with permission, from [16]). (5) Tulip-shaped gripper structure with embedded actuators and electroactive material (© [2020] John Wiley and Sons. Reprinted, with permission, from [17]). (6) Micro-actuators having a highly cross linked network (© [2022] John Wiley and Sons. Reprinted, with permission, from [18]). (7) Highly deformable microtubes made using direct peeling-based technique (© [2015] Nature Publishing Group. Reprinted, with permission, from [19]). (8) 3D printed molds for pneumatic actuation (© [2015] Elsevier. Reprinted, with permission, from [20]). (9) Miniaturized smart soft composite actuator made using two-photon polymerization (© [2007] AIP Publishing. Reprinted, with permission, from [21]).

1.1.1 Remote actuation

Most robots that integrate remote actuation use soft materials that can be programmed to change their physical and mechanical properties such as stiffness and shape by externally applied sources of energy. These sources can be light, heat, chemicals, optical, magnetic and electrical fields [13, 22, 23]. One can refer to the comparison of magnetic and optical actuation methods as the most widely used actuation methods in mobile microrobotics [24]. A weak and nonharmful magnetic field can affect the soft robot configuration remotely [25–27]. Magnetic actuation is widely used for untethered microrobots and soft continuum manipulators [28]. Magnetic fields can achieve complex shape variation in the soft material magnetically actuated on the workspace of the MNS (Magnetic Navigation System) [11, 14, 29–31]. However, individual or selective stimulation is challenging. Light driven soft microrobots, have the advantage of selective and parallel stimulation [15, 16, 32–34]. The main disadvantage is the limitation of depth penetration in some environments. As for thermal actuation, when the temperature gradient is intrinsic to environment, no external stimulus required [35]. This actuation solution is easy to implement but it can have toxic or inactivating effects.

1.1.2 Contact actuation

The contact soft micro-actuator can be classified in two main categories: (i) the artificial muscles based on active materials and (ii) the fluidic actuators based on hydraulic or pneumatic actuation.

Electroactive polymers (EAPs) are one of the most popular artificial muscle. These actuators change in dimensions or shape due to electrical stimulation. Most of these actuators can be classified into two categories namely; dielectric elastomers (DEAs) and Ionic polymer-metal composites (IPMCs). The advantages of using this type of actuator in soft robotics are large deformations, high dynamics, and light weight and low cost [36]. Another advantage is the self-sensing capability [37]. However, actuating these DEAs require high voltages in the order of kV which could restrict the applications (e.g. in vivo explorations) [38].

Hydraulically amplified self-healing electrostatic (HASEL) actuators is an other type artificial muscles used in soft microrobots. HASEL actuators use two flexible layers and liquid dielectric [39]. They can generate large strains and high dynamics. However, like DEA, HASEL actuators require high voltages (20 kV) [39, 40].

Another widely used type of artificial muscles is the shape memory materials (SMAs). These actuators are based on several different type of materials: (i) shape memory alloys [17], (ii) shape memory polymers and (iii) shape memory hybrid [41, 42]. Recent reviews about SMAs is detailed in [43, 44].

Fluidic actuators is another way to perform actuation in soft miniaturized robotics and especially when considering interactions with living organs and fragile objects [19]. Fluidic actuators can be soft and biocompatible. Mainly, three types of actuators have been reported in literature: elongation [45], bending [20], and torsion [46]. Thus, large deflection can be obtained by employing hyperelastic polymers such as polydimethylsiloxane (PDMS), parylene and polyimide.

1.2 Soft Miniaturized Robot Design

Several soft robotic designs have been proposed in literature and most of these designs have been developed by trial and error approach [47]. Other advanced design approaches are also available: (i) methods adapted from classical methods in mechanism design [48], (ii) Topological optimization methods [49]. Researchers are currently working on the design of soft mechanisms for a desired task (positioning, grasping, or locomotion) combining multiple soft actuators based on mathematical models.

Defining the optimal design of a soft Miniaturized robot is still a challenge in which some recent works have been published. We propose to classify robot designs in 4 categories: mobile, serial, parallel, and hybrid as summarized in Figure 2 with some examples.

First type of soft miniaturized robots are devices capable of swimming in liquids or crawl in soil by harvesting energy from external energy sources [50]. Researchers are building the design of these micromechanisms at small scale inspired by the agility and plasticity observed in nature. These microswimmers mechanisms have been significantly impacted by the advances in novel microfabrication techniques such as two-photon polymerization and 3D stereolithography. Multiple complex designs have been presented such as helical structure [51–53], cargo [54], and molecular [55], etc. These mechanisms can navigate by exhibit changing body forms or shapes. Some swimming microrobots use potential energy by storing energy in deformation and when stretched the robot move. Other soft robots use stick-slip principle to move [56].

Second type of soft miniaturized robots are microstructures able to perform complex manipulation tasks with high dexterity such as manipulation and assembly. When considering a soft robot with multiple degrees of freedom, at least two actuators have to be wisely mounted to a structure to create the desired complex motion. At small scale, most of manipulation robots can be classified into 3 sub-categories: serial structures, parallel structures and hybrid robots as shown in Figure 2. By joining soft and rigid elements in series, the obtained structure is serial with multiple DoF [57, 58]. However, designing and actuating this type of structure remain difficult. Continuum robots with soft or flexible bodies are often employed in minimally invasive access since it is an ideal solution to the anatomical constraints [59, 60]. These robots are composed of tubes assembled concentrically. The control of these robots still a challenge because of the elastic interactions between tubes, causing overall structure to twist and bend.

An interesting method to develop 3D architecture with multiple DoF is creating controlled folding shapes. Designing robot structure with two or more materials with different mechanical properties will undergoes deformations that lead to folding or buckling. Researchers exploited this origami-like property to reproduce well known conventional robotic structures at small scale such as the revolute joint. These technique have been employed in different robotic structures as shown in Figure 2. In [61], each universal joint was replaced with two perpendicular revolute flexible joints so it could provide 2-DoF rotations. The mechanism was fabricated using 12.5 µm thickness polyimide flexible film sandwiched between two rigid layers of carbon fiber.

Another origami-like soft robot for laser microsurgery have been presented in [62]. Piezoelectric cantilevers have been attached to a soft miniature parallel structure to generate two rotational DoFs.

As Origami-like soft robots are mostly based on soft revolute joints, this method becomes difficult to employ design complex structures. In such a case, compliant elastomer articulations enabling to build soft spherical joints are used. As an example, the robots in [63, 64] have been made with a rigid silicon structure and soft joint (Polydimethylsiloxane 'PDMS') using MEMS fabrication process. To generate the 7 DoF, one of the robots has been actuated using 8 piezoelectric actuators placed on the fixed base.

Multiple DoF can be obtained by combining multiple actuators in parallel. Hand like with multiple DoF soft robot can be obtained such as in [65, 66]. Each finger is a balloon structure consists of bonded two films having different stiffness.

2 Robot's fabrication

In its early days, miniaturized robotics has benefited from cleanroom manufacturing to demonstrate original and breakthrough proofs of concept. This approach has enabled to fabricate 2D or 2.5D microrobots. The recent evolution of 3D printing has allowed for rapid development without the often heavy constraints of the clean room including the variety of equipment and qualified staff. Next, the challenges of miniaturized robot fabrication will be presented, then the fabrication methods will be discussed with an identification of the challenges to be addressed.

2.1 Microfabrication challenges

The challenges of fabrication lie primarily in the capability at small scales to obtain 2D or 3D structures, then the properties of the material (Young's modulus, Poisson ration, tensile strength, etc.), the scale, and the precision of the patterns in the intended structure. Miniaturized robotics, in general, covers

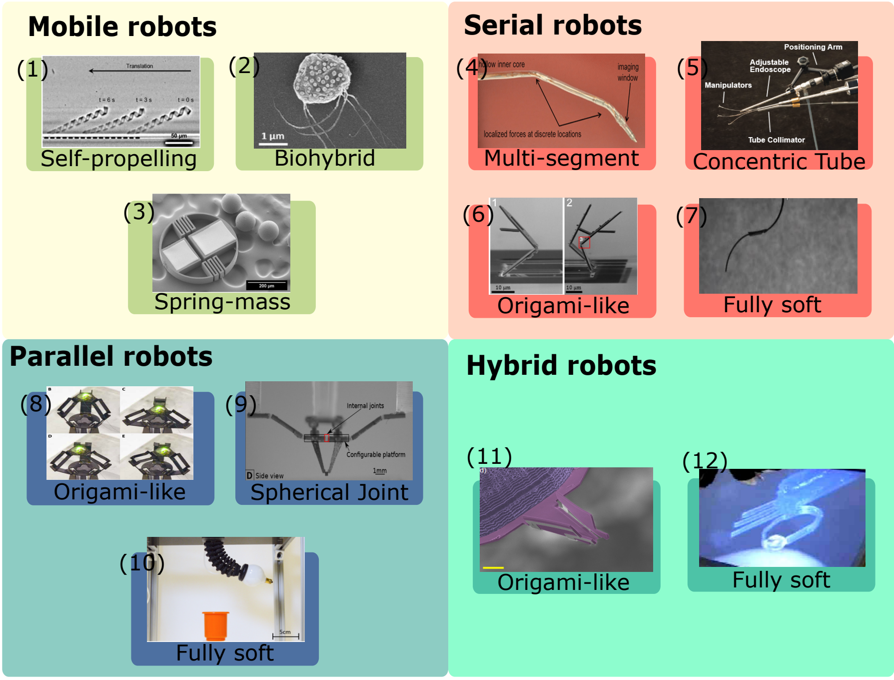

Fig. 2 Miniaturized soft robots classified into 4 categories **Mobile robots:** (1) Self-propulsion microgels dynamically controlled its shape through photothermal heating (© [2017] John Wiley and Sons. Reprinted, with permission, from [53]) (2) Attachment of liposomes to MTB (MTB.LP) through carbodiimide chemistry (© [2014] American Chemical Society. Reprinted, with permission, from[67]) (3) PolyMite: wireless resonant magnetic microrobot (© [2014] IEEE. Reprinted, with permission, from [56]). **Serial robots:** (4) Multi-degree-of-freedom discretely actuated steerable cannula with shape memory alloy (SMA) actuator (© [2012] SAGE Publications. Reprinted, with permission, from [57]). (5) Robotic system for transnasal surgery featuring concentric tube manipulator (© [2021] SAGE Publications. Reprinted, with permission, from [59]). (6) A polyarticulated structure including 3 joints where compliant joints are made of Silica by Focused Ion Beam (FIB) folding (© [2021] IEEE. Reprinted, with permission, from [68]). (7) Millimeter-size Continuum Soft Robot (CSR) consists of active flexible polymer actuator-based on multisegment [69]. **Parallel robots:** (8) Millimeter-scale Delta robot operates with high speed and precision (© [2018] AAAS. Reprinted, with permission, from [61]). (9) MiGriBot: Miniaturized parallel robot with a configurable platform and soft joints, designed to perform pick-and-place operations at the microscale (© [2022] AAAS. Reprinted, with permission, from[63]). (10) 3D printed soft fluidic parallel robot with 3 DoF (© [2017] IEEE. Reprinted, with permission, from [70]). **Hybrid robots:** (11) Microrobotic structure with integrated gripping and embedded electrothermal actuation (© [2021] John Wiley and Sons. Reprinted, with permission, from [9]) (12) Pneumatic PDMS micro hand as an end-effector of robot and miniaturized parallel link robot (© [2006] IEEE. Reprinted, with permission, from [65]).

several scales including meso-scale (100's of μm to a few mm's), micro-scale (10's of μm to 100's of μm), and nano-scale (nm). The choice of fabrication method often begins with the material being considered. Indeed, this will induce exclusions among all available processes. Soft material Young's modulus is in the range of 10^4–10^9 Pa but some high elastic modulus materials (glass, Au, NiTi, Al, etc.) have interesting behavior at micro- and nano-scale [9, 68, 71]. The stability (variation of mechanical and chemical characteristics) of the manufactured objects is essential to guarantee long-term robotic performance or at least repeatability. One has also to consider the working environment of the final miniature robot which can be air, liquid, and vacuum according the application requirements. Considering the object shape, the trade-off between the object size and the resolution of patterns has to be considered. For limited footprint, it is possible to fabricate dense line patterns in silicon and metal lift-off features at sub-20 nm feature size by thermal scanning probe lithography (t-SPL) [72]. Conversely, it is possible to fabricate tens *mm* object size but the feature tolerance is limited to tens of μm with stereolithography. Consequently, the relative accuracy (feature tolerance or feature resolution/object size or robot dimension) becomes a key criteria.

We propose to classify the existing manufacturing techniques into 3 categories: micromachining, 3D printing, and micro-assembly. Each technique will be briefly discussed in the following and linked to the presented robots in Section 1.

2.2 Fabrication methods

2.2.1 Micromachining

Micromachining corresponds to the different fabrication processes of devices with at least some of their dimension is in micrometer range. It can also named as microfabrication, micromanufacturing, and Micro-Electro-Mechanical Systems (MEMS). It includes the following main manufacturing techniques [73]: chemical-etching, template-guided electroplating, micromolding, template-assisted layer-by-layer assembly, electrodischarge machining (EDM), laser machining, and 2D photolithography. By combining lithography, electroplating, and molding, it is possible to obtain LIGA (German acronym for *Lithographie, Galvanoformung, Abformung*) which creates high-aspect-ratio microstructures [74]. MEMS processes are largely used in semiconductors or microelectric manufacturing for batch fabrication. As previously shown, some microrobots with compliant parts have been fabricated by MEMS processes as parallel robot [63], resonant wireless microrobot [75], digital microrobots [76], and helical nanobelt swimmer [77].

2.2.2 3D printing

3D printing or additive manufacturing (AM) has increased the possibility to fabricate complex, modular and configurable soft miniaturized robots [5]. Figure 3 shows that various 3D printing processes have been used to fabricate miniaturized soft robots but the relative accuracy defines very little overlap area. Apart from selective laser sintering (SLS), all other processes including fused deposition modeling (FDM), direct ink writing (DIW), vat photopolymerization, and material jetting are mainly based on elastomers, polymers, hydrogels, composites, and biomaterials [78–81]. FDM was extensively used for soft robots at macro-scale [80, 82, 83]. The limitation in the possible resolution limits its use to soft miniaturized robotics. Conversely, vat photopolymerization, and two photon lithography constitute versatile and fast prototyping way to obtain 3D structures at meso and micro-scale with high spatial resolution suitable. Vat photopolymerization includes stereolithography (SLA), Digital Light Processing (DLP), and Continuous Digital Light Processing (CDLP). These processes have been used to fabricate soft miniature robots for pneumatic actuators with restraint beam design [84], active catheter [85], and milli-swimmers [86].To complete the lower scale (micro and nanometer), two photon lithography has become a gold standard process for the printing of precise and complex 3D structures [5, 87]. For the development of new generation of soft miniaturized robots, multi-functional polymers have to be developed to perform actuation and/or sensing in order to achieve robotic tasks as positioning, locomotion, and grasping [88].

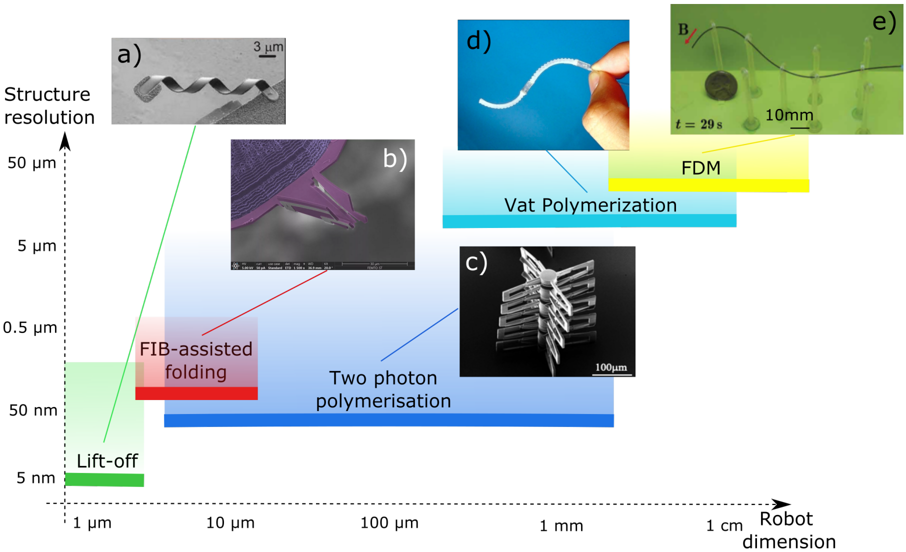

Fig. 3 Structure resolution versus robot dimension for the considered 3D printing processes, lift-off, and FIB-assisted folding: a) helical nanobelt swimmer (© [2022] American Chemical Society. Reprinted, with permission, from [89]), b) nanogripper [9], c) metamaterial soft microrobot (© [2014] Nature Publishing Group. Reprinted, with permission, from [10]), d) two sections pressure driven microcatheter (© [2016] IEEE. Reprinted, with permission, from [49]), and e) ferromagnetic soft continuum robot (© [2019] AAAS. Reprinted, with permission, from [90]).

2.2.3 Micro-assembly

Micro-assembly can be used to fabricate 3D microstructures with flexible parts [91, 92]. Two approaches are usually proposed: self-assembly [93] and robotic assembly [94]. The latter is the common approach based on use of a gripper on robotic system which performs a pick-and-place task. Self-assembly is an alternative which relies on the autonomous organization of components into ordered patterns or structures thanks to physics [95]. For objects smaller than 10 μm size, robotic micro-assembly can be performed inside Scanning Electron Microscope (SEM) [96] and augmented by using Focused-Ion-Beam as etching tool for complex tasks demonstrated on microhouse on fiber tip [97] and nanogripper nanogripper [9] (see Figure 3).

3 Modeling and Control Strategies

Miniature soft robots are exciting for multiple applications such search and inspection or medical, which involve a high level of uncertainty especially when interacting with external environment. Best way for modeling and controlling these robots is still an open question in scientific and research field, since it depends on many factors such as actuation and sensing method, limited onboard space, dynamics and mechanical properties of the robot. Hence, soft materials exhibit highly nonlinear response making the development of a general methodology for modeling and controlling these robots an exciting research challenge.

3.1 Soft Miniaturized Robot Modeling

Developing an accurate model for a given soft robot with low execution time is the key for optimal control, such as trajectory generation, optimization and tracking and collision avoidance. Proposed models in literature can be loosely classified into two general categories; physics-based and data-driven [98].

3.1.1 Physical based modeling

When the robot is considered as a continuum mechanism (like concentric tube robots), deformable beam (rod) theory can be employed as a very fast model [99]. These models are based on Euler-Bernoulli [100–102], Timoshenko [103], Kirchoff [104] or Cosserat [99] rod theory. In the same category, we can also find Finite Element Method (FEM) [26]. FEM is a powerful tool for modeling and simulating soft actuators and robots with high non-linearity [105, 106]. However, it remains computation-intensive and dependent on the numbers of nodes (meshes) which affects the performances of results. Thus, a compromise has to be made to choose between precision and simulation execution time. These techniques have been used to model, optimize and control soft robots at different scales and showed effective performances. Thus, to consider for unforeseen variations in mechanical variation of soft materials, the parameters of these models have to be tuned to better fit the reality.

3.1.2 Data-based modeling

Whatever the scale considered, in soft-robotics, the high number of Degree of Freedom (DOF), the non-linear behaviour, the time varying properties of polymers and the heterogeneous stiffness make difficult to set-up a reliable model of the soft-robot [107]. In micro-nanoscale, the challenge is even higher as (i) the environment variation (humidity, temperature, etc.) and (ii) the stochastic variability during fabrication have both a strong impact of the soft micro-actuator behaviour [108].

Data driven for soft robots modeling often learn and generates a robot's inverse kinematics [109, 110]. Several approaches have consequently emerged using data-based modeling. Thus, due to its hyper redundant structure, soft robot model may lead to infinite solutions for a given position of the end effector. Models issues from learning techniques will return an interpolation of these multiple valid possible solutions [111].

The first approach consists in probabilistic learning approaches using Bayesian optimization (BO) and Gaussian processes (GPs). It has been, for example, tested on millimeter-scale magnetic walking soft robots in order to optimize the control parameters [14]. This approach enables to improve the performances of the controller with a limited numbers of tests. As an example, von Rohr et al. shows that the locomotion performance of a light-controlled soft microrobot can be improved of 115% in only 20 tests [32].

The second approach uses machine learning approaches combining both a precomputed off-line learning on a FEA model and on-line learning. It enables to learn first the model of a soft-robot and to perform gradient-based optimization to find the control input. Bern et al tests this solution on a expandable polyurethane foam soft robot using a neural network framework with sigmoid activation functions [111]. It is also possible to directly learn the control parameters as illustrated by Lee et al. on a pneumatic soft millimeter-scale endoscope [112].

3.2 Control strategies

In a general way, three main strategies are used to control soft miniaturized robots (see Fig. 4). For simple applications, it is possible to use a on/off control strategies in which the control parameter (e.g. light intensity in a thermoresponsive gel) switches between two defined values. The second level of control strategies is to use a continuous control parameter (e.g. external magnetic field in magnetic microcatheter) in open loop and a feedforward controller knowing the model of the microrobots. Some soft miniature robots are also controlled using closed loop controllers using exteroceptive or proprioceptive sensors.

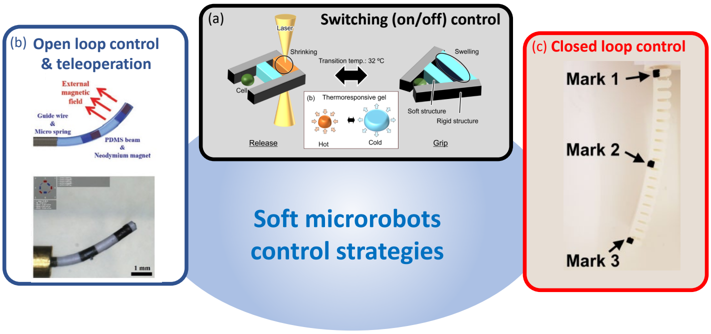

Fig. 4 Synthesis of the control strategies used for soft miniaturized robots: (a) switching (on/off) control (e.g. a bistable gripper actuated with a thermoresponsive gel) © [2022] MDPI. Reprinted, with permission, from [113]; (b) open loop control and teleoperation (e.g. a compliant catheter) © [2019] Mary Ann Liebert Inc. Publishers. Reprinted, with permission, from [26]; (c) Closed loop control (e.g. a pneumatic actuator controlled using visual servoing) © [2020] IEEE. Reprinted, with permission, from [114].

3.2.1 Switching control

The switching control consists in using two values of the control inputs to switch from one position A to a position B. It can be used typically to actuate a gripper switching between an open position and a closed position. This simple control strategy is particularly relevant when using a soft miniaturized robot. Indeed, the compliance of the robot can be used to compensate some external disturbances (such as the variation of a micro-objet size to grasp in case of a microgripper).

This strategy is used to control bistable micro-actuators. The typical approach is to use a bistable mechanism with snap though enables to define two (or multiple) stable positions. Various actuators can be used to switch from one position to another such as acoustic actuators [23] or thermal actuators [115, 116]. The actuator can be also itself bistable without requiring a mechanical bistable mechanisms. It is typically the case of the thermoresponsive gel in which the transition from state to another can be reached in few Kelvin [113] or hydrogels whose deformations have two asymptotic positions when placing respectively in air and in water [117].

The on/off actuation is also particularly relevant for controlling drug microcarriers opening to deliver locally a dose a drug for in-vivo applications. Several prototypes have been proposed such as an opening controlled by light [118] or a magnetic actuated pH-responsive hydrogel-based soft micro-robot for targeted drug delivery [119]. As it does not require any sensor feedback, this control strategy can also be extended to nanoscale applications using, for example, photo-Controlled Ferroelectric-Based Nanoactuators [30].

3.2.2 Open loop control

The second control strategy consists in open loop control where the soft miniaturized robot is controlled without visual servoing. It is one of the most simple control strategy particularly relevant for teleoperation and when no precise automatic cycles are required. The operator will adapt himself the control inputs in order to reach the desired position or trajectory despite the disturbances.

The simplest implementation consists in controlling in teleoperation the robot directly using the physical control input. As an example, Lee et al, perform a grasping operations using a soft-microgripper based on Shape Memory Alloy by controlling directly the actuator heating [17]. It can be also used in remote actuation such as controlling a swimming photoresponsive soft-robot controlling the light input directly [15].

When the behaviour linking the physical input and the deformation/displacement of a soft-robot becomes complex, it could be difficult for the operator to define the right input to reach the desired position. In such a case, feed-forward control strategies are proposed. The operator defines a required position or velocity and the feed-forward controller based on a model can define the input to apply to reach the goal. Jeon et al. use this strategy to control a magnetically controlled soft microrobot based on a model mapping deformation of the soft microrobot [26]. In case of micro-aerial softrobot feedforward control is used to reach open loop control stable flight [120].

3.2.3 Closed loop control

Some more advanced devices are based on closed loop control enabling to guarantee a trajectory or a final position despite some external disturbances. The feedback is usually based on visual feedback measuring (i) the deformation of the robot or (ii) the movement induced by the deformation (in case of swimming soft microrobots).

In the first case, the visual servoing can be based on the measurement of the whole deformation or only the displacement of one point on the soft robot. As an example, Ji et al. propose to control a pneumatic micro-actuator using visual servoing based a multipoint tracking enabling to measure the whole deformation of the robot [114]. It could enable to identify both the position of the end-effector of the robot and the applied force. When only the position of the end effector has to be controlled, the most efficient way is to measure only this position (in spite of the whole deformation). It has been tested, for example, on a polypyrole based soft microrobot dedicated to in-vivo applications [121].

When controlling the trajectory of a swimming soft microrobot in closed loop, the strategy consists in measuring the position and whole orientation of the robot in spite of its deformation. Indeed, the deformation itself could be difficult to track considering both the small deformation amplitude and the frequency of the amplitude (several Hz). This approach is mostly used to control magnetic soft microrobot based on visual servoing [13, 122]. Dong et al. also shows that it was possible to control the trajectory of a soft swimming biorobot (a living nematode worm) using light stimulus and closed loop control [33].

4 Future Challenges

4.1 Promoting new designs and actuation principles

In most cases, designing soft microrobots in an optimal way is still an open challenge which may require to explore, more widely, some optimization tools (e.g. topological optimization) or artificial intelligent tools. Design is also closely linked with the actuation principles and some new active materials are still under development. As an example, researchers are increasingly exploring the use of smart polymers, such as thermomechanical metamaterials, multi-domain soft magnetic polymers, and biocompatible gels. These materials hold promise in enhancing the capabilities of future miniature robots and influencing their design, and performances. For instance, smart polymers can enable complex shape-shifting capabilities, opening new avenues for innovative soft robot designs. Moreover, when considering micrometric scales, the development of multi-functional polymers compatible with 3D micropriting technologies is a big challenge in order to fabricate complex soft microrobots in one step of printing without assembly steps.

4.2 Improving the repeatability of the soft microrobots

One of the future challenges is to enhance the performances of the soft microrobots and especially the repeatability. It deals with both (i) the design and the fabrication capabilities and (ii) the embedded sensors and control strategy.

As the soft microrobots require thin deformable parts, the robot accuracy and repeatability are linked to the precision of the fabrication means (to guarantee the geometry of the soft joints) and also to the stability of the material over time (to guarantee the repeatability of the mechanical behavior of the soft joints). When looking to nanoscale or even to micrometer scale, the development of suitable fabrication principles for soft robots is still a challenge, and investigations on innovative approaches are welcomed.

Miniature soft robots will also benefit from advanced integrated sensors and feedback mechanisms. These technologies will improve their adaptability, perception, and interaction with their environment. Considering specific sensor types, such as tactile, visual, or proprioceptive sensors, and how they can be integrated into soft robots for enhanced functionality. Precise control remains a challenge due to the large deformations and numerous degrees of freedom in soft robots. Future advancements in artificial intelligence and machine learning hold promise for enhancing control algorithms for miniature soft robots. Highlight recent breakthroughs and provide examples of how AI-based control can address these complex control issues.

4.3 Toward autonomous soft microrobots

One of the highest challenges is to develop autonomous soft microrobots. In this way, addressing the challenge of power sources and energy efficiency is crucial. The development of miniature, high-capacity batteries or efficient energy harvesting methods will significantly impact the autonomy, performance, and operational duration of these robots. This advancement is essential to enable longer lasting and more capable miniature soft robots.

Moreover, coordinating multiple miniature autonomous soft robots can significantly improve productivity and precision in various applications. Explore the potential benefits of swarm robotics or team-based approaches, emphasizing scenarios where collaboration among these robots is advantageous. Discuss communication methods and coordination algorithms as key components of effective coordination.

Conclusion

In this review, we have reported classification and recent advances of miniaturized soft robots in terms of design, modeling, fabrication, and control algorithms. Fabrication process innovations have enabled to design and fabricate various miniaturized soft robots covering the full scale from millimeter to tens of μm size. The large variety of both actuation principle and robot structure enables to target several final application going from industrial pick-and-place to in-vivo biomedical operations. The future challenges deal with the soft miniaturized robot accuracy and repeatability improvement highly linked with the fabrication precision especially when looking to the nanoscale. The sensing technologies and algorithms (detection, localization, shape reconstruction) have also to be improved to better control in closed-loop the miniaturized soft robots or to provide an haptic feedback to the user, especially considering confined spaces as lab-on-chip, intracorporeal, and vacuum environment.

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Declarations
Conflicts of Interest:

The authors declare that they have no conflicts of interest.

Human and Animal Rights and Informed Consent:
This article does not contain any studies with human or animal subjects performed by any of the authors.

Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major importance

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