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RESEARCH PAPER

A holistic survey on mechatronic Systems in Micro/Nano scale with challenges and applications

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Abstract
Micro/Nano mechatronic systems might be defined as systems that include nano- or micro-scale components. These components can be sensors, actuators, and/or physical structures. Furthermore, the high-precision control laws for such small scales are important to ensure stability, accuracy, and precision in these systems. In this writing, four categories of such small-scale systems are considered by providing multifarious novel or key examples from the literature: control engineering and modeling, design and fabrication, measurement engineering, and sensor/actuator development. The applications discussed in the examples vary from nano-positioners, crucial in systems such as atomic force microscopes, to biological sensors like carbon nano-tubes that respond to chemical or molecular stimuli. It is observed that in many instances, especially in micro−/nano-robots, the categories overlap for the completion of a system that needs to be small in size, to be controllable with high accuracy, to have high precision sensing capacity, and finally to be able to carry out submillimeter measurements. Thus, a holistic point of view upon such systems is necessary for future applications. This paper does not limit the type of sensors or actuators to the industrial ones and extends the investigated examples to encompass biological sensing and actuating mechanisms that respond to chemical stimuli, proposing for the inclusion of these units in nano−/micro-mechatronic systems intended to be used in human body or other bio-environments. Several other research opportunities are discussed, challenges in the field are identified, and some propositions are put forward for future directions.

Keywords Micro-nano mechatronic systems · Micro control engineering · Nano-sensors · Nano-robots · Micro-sensors · Shape Memory Alloys

1 Introduction

Micro and nano mechatronics deals with systems that are in submillimeter scale and possess components that are remarkably small compared to their regular-sized counterparts. This sub-branch of mechatronics has a wide range of applications from micro-robotics, actuators, and sensors to biologically inspired systems that can be used for biomedical or biological purposes. The use of miniaturized mechatronic components enables the materialization of features such as high performance, low cost, low energy, light weight, and low space requirements [1]. Nano mechatronic systems might be categorized under a number of main groups: (i) nano control engineering and modeling, (ii) nano design and manufacturing, (iii) nano measurement engineering, and (iv) nano materials science (all the "micro"- equivalents also exist, leading to a categorization of micro mechatronic systems) [1].

Of course, there are important differences in physics, design, and fabrication processes between systems that operate in nano scale and those that work in micro scale. As systems transition from macro to micro, and then nano scale, despite the fact that many physical laws remain valid, the importance of surface forces increases relative to body forces and some molecular and atomic effects become considerable. This change of scales leads to different governing equations when considering thermodynamic processes [2] like heat transfer or fluid and gas flow in micro and nano scales [3]. In nano scales, quantum effects could also arise especially when electronic effects are of interest

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[4]. Even though the applications considered in the present article generally exclude such domains and current scientific and engineering literature predominantly consider micro and nano systems in the same scope, a distinction has been made between these two realms in this paper wherever applicable.

In this short review, an effort has been made to identify current status, challenges, opportunities, and applications in all the abovesaid categories. Some intriguing examples in all the mentioned categories are considered and concisely introduced. Certainly, in some cases, it is difficult to decide which category a system or application should fit into. In these instances, the main theme of that system or application is considered. For example, micro flying robots can come under all categories; but, their small size and the challenges in their design and construction justifies grouping them under the second category (ii). Or, even though new component designs are essential in nanomanipulation systems, presently, their main challenge is their control; hence, they are discussed under the first category (i).

The end of this review is to show (1) how wide the scope of micro and nano mechatronic systems has grown, (2) how research in all aspects of mechatronics, from new mechanism development to material investigation for sensor and actuator development, has contributed to the field, and (3) how many opportunities exist for further research in this multi-faceted area. An extensive review that looks at nano/micro mechatronic systems as a whole is lacking in the literature, especially, as will be seen, when such a holistic view can create new ideas by bridging different sub-fields. As there is a great potential and interest in applications of these systems in life sciences and biomedical research, wherever relevant, special attention has been given to these applications throughout the manuscript [5].

The sections of this writing are organized as follows: Section 2 is dedicated to challenges of control engineering and modeling in small scales and, besides active research topics in micro and nano robots, it covers problems associated with friction, long-range travel, hysteresis, creep and vibrations; Section 3 focuses on micro/nano design and fabrication ideas, as well as submillimeter robots in air, water, and on ground; Section 4 considers the topic of measurement in submillimeter systems; and eventually, Section 5 discusses new materials in industrial and biological applications, with an emphasis on polymers and shape-memory materials. Section 6 contains some concluding remarks on the various studies considered in this review and it strives to elucidate the connections between each two categories presented in Sections 2–5. Some research ideas are also proposed on the basis of discussions throughout this writing.

2 Nano (micro) control engineering and modeling

High precision control in nano or micro scales is of great importance in many engineering or science applications such as microscopy [6, 7], spectroscopy [8], nanomachining [9, 10]; and surface profilometry [11, 12]. Some of the challenges in nano- or micro-controlling are the management of friction, long-range travel, vibrations, hysteresis and creep. This section investigates a number of the solutions that have been proposed for dealing with these difficulties. Besides macroscopic systems that operate on micro−/nano-scales, controlling microscopic systems in micro−/nano-scales also entails challenges, which will be briefly discussed as well. An important point considering small-scale robots is that within such systems the “classical” definition of control expands to include novel methods of path tracking and manipulation that may be done by external fields (e.g., a magnetic field or light) or a kind of chemical propulsion. These systems arise again in Section 3 and will be reviewed more closely there.

2.1 Control challenges in systems operating on Nano (micro) scales

2.1.1 Friction

The friction imposed by the bearings used in many nanopositioning stages, as reported by Liu [13], as well as, other surface contacts, limits the accuracy of the system. One solution to overcome this limitation is to study the behavior of friction and to make efforts to compensate it, rather than relying simply on an estimation of the friction coefficient [13]. For example, Amthor et al. developed a full model of the pre-rolling and rolling friction based on experimental data and the Basic Maxwell Slip technique, which gives the friction force in a mass-damper-spring system as a linear combination of the displacement and the spring deformation [14].

An alternative to friction control is to manage friction by taking advantage of new hardware designs—an intersection with materials research. Coatings, such as tungsten carbide/carbon (WC/C) [15, 16] or altering the surface traits using new manufacturing techniques to give a desirable friction behavior, can better a system’s performance. An example on the fabrication of an anisotropic-friction surface was reported by Zhang et al. They used it as a solution to the sliding of the end effector on the platform that occurs during the contraction phase of a piezoelectric-driven stick-slip actuator [17]. When compared to a typical system, they were able to achieve faster responses and larger maximum output force using the same amount of applied voltage. Besides coatings, flexure bearings [18] and mag-lev [19] technology have also facilitated friction management, helping avoid complex control algorithms. Yet, both solutions are limited, due to low stroke and load capacity in the former, and high cost and complexity in the latter [20].

Thus, despite the abovementioned alternatives to friction control in recent works, the inclusion of this force in the modelling and compensation is still frequent in the design of micro- and nano-positioners. Notedly, this method leads to desirable outcomes [21–23], warranting its continuation. Still, devising novel, effective, and economic solutions to avoid friction in the first place is a demanding research topic in micro−/nano- positioning. The identified methods for control management are summarized and compared based on four essential factors in Table 1.

2.1.2 Long-range travel nanopositioning

Long-range travel is a challenge when using piezoelectric actuators—which are popular for their high precision, since they can only provide a range in order of tens of micrometers [24]. Inch-worm piezo-motors enable displacements of several millimeters, but they suffer from small output force and glitching. Similarly, one can utilize lead-screw motors for long travel; yet, the performance is compromised due to backlash, stick-slip, and insufficient resolution. As an alternative, Cheng et al. combined an ultrasonic motor, a newly-developed Laser Diffraction Grating Interferometer (LDGI), and a self-tuning PID controller, based on back-propagation neural network (BPNN), to make possible long-range nanopositioning [24]. The BPNN controller, acting in real-time, was required given the destabilizing impact of friction. The long-range travel was made possible by different modes of the ultrasonic motor and its driver, allowing both millimeter and then nanometer displacements.

One of the most widely used methods to enable long-range displacements is to utilize dual-drive (or dual-stage) mechanisms. Liu et al. used two PID controllers in two different stages to enable long stroke in one stage and high-precision positioning in the other [25]. The first controller was applied on the x and y displacements of the ball-screw stage. The second one was designed for the three-degree-of-freedom nano-stage, along x and y direction and around z axis. Awtar et al. proposed different and customized controllers for each axis of their large-range XY nanopositioning system, while considering the effect of the floor vibrations and cross-coupling disturbances [26]. In [27], using a moving magnet actuator and a flexure bearing, the same research group aimed at a friction-free, no-backlash configuration. Still, the nonlinearities in the actuator required an additional iterative learning controller.

Similar works have been reported more recently in [28, 29], with the latter achieving an extraordinary range of 50 mm (compared to a range less than 15 mm in the above-cited works). Current existing challenges in enabling long-range motions, which recent literature has focused on, include energy efficiency [30], simplifying structure assembly [31], mitigating parasitic motion [32], and of course, achieving even higher motion ranges.

2.1.3 Hysteresis, creep, and vibrations

Hysteresis and creep in piezoelectric materials impact the accuracy and repeatability of nano- and micro-manipulators. Like the case of friction, modeling-based compensation is the predominant method to deal with these nonlinearities. Open-loop scheme is especially used where integrating sensors is difficult. Rakotondrabe et al. suggested a fully open-loop control of hysteresis and creep based on inverse models in the feedforward path [33]. They used the popular Prandtl–Ishlinskii (PrI) [34] modelling approach and a dynamic linear model to respectively compensate for the hysteresis and creep effect. PrI and many other methods of modelling hysteresis are founded on weighted superposition of fundamental hysteresis operators [35]. Modified and generalized PrI models have also been proposed [36, 37] when the simple model is not adequate. For instance, as vibration is frequency-dependent, authors in [38] developed a modified, rate-dependent version of PrI to control hysteresis.

Noting that at high frequencies a feedback controller is not sufficient due to reduced open-loop gain, other feedforward methods have been studied. Namely, Bouc–Wen modelling has been the preferred method in several works due do its mathematical simplicity (using a single state variable to describe hysteresis) and being able to represent a large class of hysteresis problems [39, 40]. A Maxwell-resistive-capacitor model is more complex than a Bouc-Wen model, but it has successfully enabled hysteresis compensation both in low-frequency [41] and high-frequency [42] applications, with the inclusion of a linear component in the latter.

Table 1 Management or control of friction in systems operating on nano/micro scales: a comparison

Method	Robustness	Simplicity	Stroke & Load	Cost
Controlling Friction				
Friction Coefficient Estimation	Low	High	High	Low
Behavioral Modelling	Medium	Medium	High	Low
Avoiding Friction				
Low-friction Coating	High	High	High	Medium
Flexure bearings	High	High	Low	Medium
Mag-Lev	High	Low	Medium	High

Feedback control, in addition to feedforward inversion of these nonlinearities, have been reported in [43, 44]. At high-frequency applications, when the dynamics of the actuator cannot be ignored, dynamic compensation of hysteresis becomes important. A three-layer BPNN has been proposed to deal with the control of hysteresis in such cases [45]. As in the case of friction, where some solutions were propounded for its avoidance, a *charge drive source*, as opposed to *a voltage drive one*, has been shown to minimize hysteresis in piezoelectric actuators [46]. Table 2 compares the discussed hysteresis control or management techniques.

Regarding vibrations, which are of importance in systems that include actuators like cantilevers, different control mechanisms have been proposed. In *Zero Vibrations* method, a sequence of impulses, referred to as shapers, and an input signal are convolved to damp the oscillations [33, 47]. To avert large overshoots, either a robust input shaper [48] or more than two impulses can be employed [33].

Shifting the resonant frequency to higher values is another vibration-control technique, but it increases the operational bandwidth of the system at the cost of more stiffness and thus lower travel range. Therefore, damping of resonant modes using controllers to bypass the mentioned problem is still an active research topic. Methods for vibration or damping control used in micro- or nano-systems include integral force feedback (IFF) [49], positive-position feedback (PPF) [50], polynomial-based control (PoBC) [54], integral resonant control (IRC) [52], and active or passive shunt control [53, 54] .

IFF utilizes an integral controller to damp vibrations and it provides a clear solution for the controller, guaranteeing simplicity. It has also been shown to be robust as its performance is not compromised when the resonant frequency of the system is shifted [48]. Similarly, PoBC is insensitive to resonant frequency shift, but in the presence of an integrator controller, the speed bandwidth of the vibration-causing components (e.g., scanner) is limited. In [55], the authors combine that method with an inversion-based feedforward technique to overcome the bandwidth limitation. On top of robustness to resonance variations, IRC is capable of damping multiple resonant modes [52].

PPF is also simple to implement and its transfer function is quite steep (40 dB/decade) at high frequencies, which is essential in dealing with sensor noise [50]. However, in low-frequency vibrations and around resonant frequencies, PPF's performance is degraded [51]. In shunt control, the principle is to measure the output charge on the piezoelectric element and regulate the input voltage using pertinent controllers (such as H_2 and H_∞ in [53]) to damp resonant vibrational modes. Since this method does not need any feedback sensor, it does not suffer from sensor noise, which is a considerable advantage over other techniques [54]. Passive shunts, which only use resistor-inductor-capacitor networks, are sensitive to frequency shift, a drawback that can be compensated for by active shunts that utilize an external energy source. All the above approaches for resonance control are compared based on three main factors in Table 3.

Simultaneous control of multiple effects is a challenge, as can be seen in compensation of tracking accuracy and vibration damping [56], or hysteresis, resonance and disturbance [57] at the same time.

2.2 Control challenges in Nano-(micro-)scaled systems

The previous subsection focused on macro-systems that operated on micro or nano scales. What about control in systems that are submillimeter themselves? As will be discussed, among these, flapping wing micro air vehicles (FWMAVs) are some of the most prominent. Maintaining stability during flight, particularly in the presence of disturbance, and path tracking are two of the existing control challenges for these vehicles. Among the proposed solutions, the following can be identified: (1) Adaptive neural network control with disturbance observer (trajectory tracking) [58], (2) general regression neural network control (trajectory tracking) [59], (3) PID control (hovering and forward motion [60], as well as, steering using the tunable impedance method [61]), (4) PI control (biharmonic amplitude and bias modulation (BABM) for

Table 2 Management or control of hysteresis/creep in systems operating on nano/micro scales: a comparison

Method	Performance in High Frequencies	Simplicity
Controlling Hysteresis/Creep		
Feedforward		
Prandtl–Ishlinskii	Low	Medium
Bouc-Wen	Low	High
Maxwell-resistive-capacitor	High	Low
Feedback and feedforward		
BPNN	High	Low
Minimizing Hysteresis/Creep		
Charge-Drive Force	High	High

Table 3 Resonance control in systems operating on nano/micro scales: a comparison

Method	Sensitivity to resonant shift	Multiple-resonance damping	Sensitivity to Sensor Noise
IFF	No	No	Yes
PPF	Yes	No	No
PoBC	No	No	Yes
IRC	No	Yes	Yes
Passive Shunt	Yes	Yes	Yes
Active Shunt	No	Yes	No

wing angle control [61, 62]), and (5) LQR control (for hovering and forward motion, using the extended unsteady vortex lattice method for wings) [63]. What is clear from the literature is that flight control is still an open problem in the field of FWMAVs.

Similar challenges exist for on-ground and minute water robots (Section 3), but they have not been explored as widely as air ones. Also, many novel ground microrobots are often controlled by external fields and operate at low speeds, thus hardships like stability and maneuver rarely arise in controlling them. But for finned swimming microrobots, control is a live challenge and schemes like dual-loop nonlinear feedback [64], and neuro-fuzzy and differential flatness [65] have been proposed for their stabilization and path tracking.

In nanorobotics, proportional to the size of components where many classical control methods may not be usable, most attention has been focused on using external fields. In these cases, instead of directly controlling components such as motors, the actuating field is controlled to generate a desirable output. To track these robots in environments such as blood or other internal organs, usually an efficient, real-time imaging methods is required. Fluorescent-based, magnetic resonance, and ultrasound imaging have all been reported as modalities to provide the feedback needed to track nanorobots [66]. These robots are best suited for in vivo applications and thus many of the recent articles in this field involve controlling nanorobots inside living tissues, especially fluids.

Among recent works in this area, in an unprecedented report, Liang and Fan used visible light to actuate semiconductor Si "nanomotors." The speed and direction of these motors are proportional to the light intensity and the AC frequency of the E-field [67]. Magnetic fields are investigated more commonly to control and actuate nanorobots. In their recent article [68], Betal et al. report a "magnetoelectric" nanorobot that is capable of following paths, cell targeting, and even cell permeation, in response to controlled magnetic fields. Another group developed a semi-autonomous, oxygen-propelled nanorobot that also can be controlled and directed by external magnetic fields. This robot uses an oxygen-producing chemical reaction inside the blood to propel itself [69]. One other novel idea is the use of electromagnetic heating to actuate DNA origami robots to release their payloads. The authors have coupled this design with EEG signals from the brain to enable remote activation of the electromagnetic fields, paving the way for automatic drug delivery as a response to certain disease-related brain waves [70]. Undoubtedly, similar studies have been reported for microrobots, including the use of magnetic fields to steer a soft robot in a vascular phantom [71], and a swimming, rigid robot equipped with disk-shaped paddles that can achieve relatively high speeds [72].

In almost all of the above examples, the design of the robot and its constituent materials is a crucial factor so that it can respond to external stimuli in a desired way. Thus, areas of research in submillimeter robot control include the development of new materials with multiple modes of actuation; investigation into new actuating fields and how factors such as intensity, frequency, and polarization affect control actions; and enhancements in maneuverability and capabilities needed in biological environments including penetration, detection, cutting, attraction, repulsion, and so on.

Even though many articles have used open-loop control schemes to steer magnetically-driven micro and nano robots, some closed-loop schemes can be found in the literature as well. Model-based feedback control of a microrobot to operate in a fluid environment [73], closed-loop control of a microbot to move along predesigned paths using two cameras [74], vision-based closed-loop control of microrobot to offset perturbances [75], and vision-based feedback control of multiple microrobots for 3D path tracking [76] are among these. Closed-loop schemes are mostly useful in ex vivo applications like lab-on-chips where the behavior of the robot can be monitored. But upon finding methods to get real-time feedback from in vivo robots, closed-loop methods will provide considerable benefits for tasks that need high precision. Figure 1 summarizes some of the control and control-related challenges and research opportunities in micro and nano systems.

3 Nano (micro) design and manufacturing

Typically, as seen in [25, 26], the development of new, or enhancing the performance of already-existing systems might involve not only novel control schemes, but also new production techniques. Thus, nano- or micro-design and

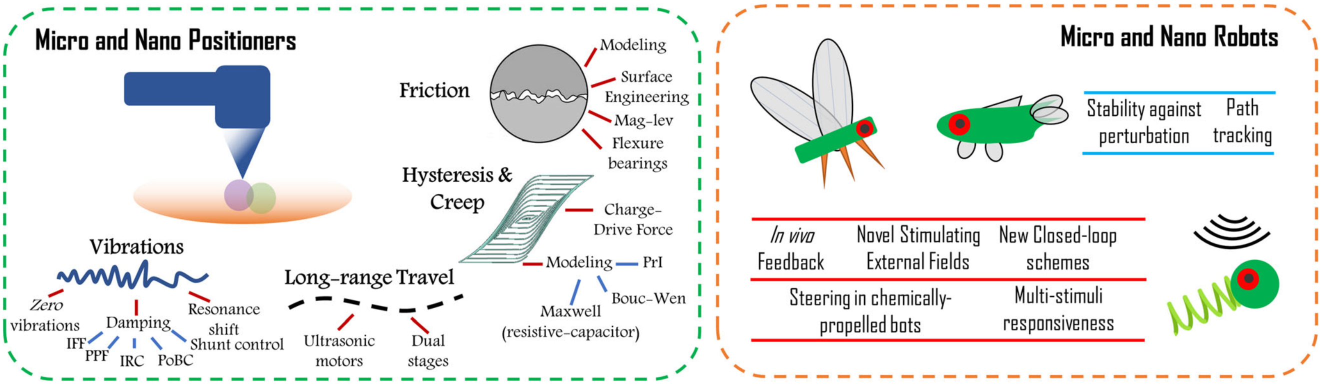

Fig. 1 Control and control-related challenges and active topics in the field of micro/nano mechatronics systems and robots

manufacturing might be viewed as methods to improve the performance of systems made to operate in micro and nano scales. They may also be seen as the design and making of micro- or nano-scale systems themselves and their minute components. In this section, an emphasis is laid on improving mechanisms or components, while some systems in submillimeter scales are introduced.

3.1 Novel designs in Nano-(micro-)manipulation systems

Long-range motion (whose control problems were considered in Subsection 2.1.2) and displacement amplification have been subjects of interest in small-scale positioning systems. Both goals can be achieved by novel mechanical designs in the system's structure, without the need for additional complex algorithms. Therefore, the innovations in such designs are worthwhile to investigate.

To have a large range in nanopositioning, Kim et al. introduced a symmetric flexure-based mechanism that acts as a self-guided displacement amplifier [77]. Incorporating a motion guide in the positioner ensures displacement in the desired direction—with minimum parasitic motion—and using displacement amplification can increase the motion range of piezoelectric actuators from tens of microns to hundreds of microns or more [77]. Chu et al. used lever-type and toggle mechanisms and high-precision cylindrical rails as guides to achieve long-range travel through motion amplification and to reduce side motions, in order, in their developed micro-positioner [78]. Other solutions for range amplification encompass using circular flexure hinges in lieu of rotation joints [79], hydraulic mechanisms [80], bridge-type flexure hinges [81], H-shaped structures [82], and a compliant stage with two parallel amplifying mechanisms [83]. The amplifier introduced in [80] was able to magnify the displacement by fifteen-fold and its application in rewritable Braille cells was demonstrated. Among the above techniques, the choice of one over the other is contingent upon the size of the system and its usage.

3.2 New designs and fabrication techniques in MEMS

Developing components, such as gears and grippers, at nano and micro scales, require inventive solutions in MEMS and other production methods. Therefore, one active topic of research is devising new fabrication techniques that allow the realization of new mechanical parts.

Among the recent works, using pure and surfactant-added TMAH to fabricate new shapes of both fixed and suspended parts, with only one photolithography step [84]; using micro-electrical discharge machining, in addition to soft lithography, to build micro metallic parts of high surface quality [85]; and combining hot-filament chemical vapor deposition (HFCVD) with inductively coupled plasma (ICP) etching to fabricate nanocrystalline diamond parts [86] can be mentioned.

Additionally, many research articles have concentrated on developing novel parts that can substantially contribute to design and fabrication of micro systems. These include microgrippers (bulk micromachining) [90], micromirrors (bulk micromachining) [91], micro-gears (lithography in a microchannel) [92], micro-thrusters (high temperature co-fired ceramic technology) [93], micro-pumps (bulk and surface micromachining and mold replication techniques) [94], and micro-accelerators (surface micromachining) [95].

Another exciting and novel approach is two-photon crosslinking (TPC) or direct-laser writing on photosensitive material. This technology enables fabrication of complex geometries in submillimeter scales, like 3D microbots for cell transportation [87], as well as chemical functionalization of components, like a micro-swimmer propelled by hydrogen peroxide as a bubble-generating chemical fuel [88]. Therefore, TPC is a perfect fabrication method for biological applications, where precise and goal-specific shaping of in vivo microbots is desired. Certainly, the integration of

MEMS patterning and direct laser writing is also possible and is being explored [89].

Devising new technologies to facilitate development of essential and highly functional parts for micro/nano machines is still an open research area.

3.3 Submillimeter mechatronic systems

One appealing branch of micro-manufacturing is the development of submillimeter robots. This area might be broken into categories based on the ambient where the robots are intended to operate: (1) air, (2) on ground, (3) water or other fluids. Briefly, these categories are reviewed in this subsection, with Fig. 2 illustrating an outline of the main subjects regarding these robots and their link to MEMS and TPC technology (previous subsection):

3.3.1 In air

Many studies have investigated the fabrication and control of micro air vehicles that use flapping wings; robots that are inspired by flying insects [96]. These vehicles are valuable in the sense that they mimic the mechanism of fly in tiny creatures in nature and provide an insight into how flying takes place naturally. The actuation of these vehicles as well as power transmission and wing design are critical in their performance.

Table 4 lists several recent studies dedicated to novel or optimized design of FWMAVs, with the important features of each work highlighted. Looking into these recent works on FWMAVs reveals that the active areas of research in this field, which still present challenges for researchers, include wing design, structural optimization, enhancement of maneuverability through smart design and control techniques, energy optimization, and extension of applications to new arenas. These will be briefly discussed in the following.

- *Wing design and structural optimization*: On wing design, there are interesting guide-like research works, such as [104], that give a methodology for wing optimal sizing. Moreover, wing designs inspired by birds and insects have gained momentum in recent years, as seen in [99, 108]. String-based wings have also been proposed, having the distinct advantage of being lighter than rigid wings [98]. In optimizing the structure of FWMAVs, wings are always an important factor [106], alongside with gear and motor holder design, with an emphasis on weight minimization [101]. Efforts towards minimizing weight, while keeping autonomy, is a live research topic [102]. The role of self-assembly (or "pop-up") MEMS in the structural development of FWMAVs deserves further investigation [110].
- *Hover and Maneuver*: Improving hover has been the topic of multiple works in the recent years, focused on the pitching motion—simple-harmonic versus bio-inspired [111], onboard sensing and PID control [112], and spring-assisted transmission for partial elastic storage [113]. Precise and optimum control of wing angle and speed are also important during transition between various statuses, as shown in [114], for transmuting from hover to forward motion. Path tracking has been achieved with learning-based methods using ground stations (in connection with the FWMAV) and model-free [115] and model-based non-linear dynamics [115, 116]. Extreme hummingbird-like maneuvers, during which model-based control is inaccurate, have been reported by reinforcement-learning approaches and only two actuators [116].

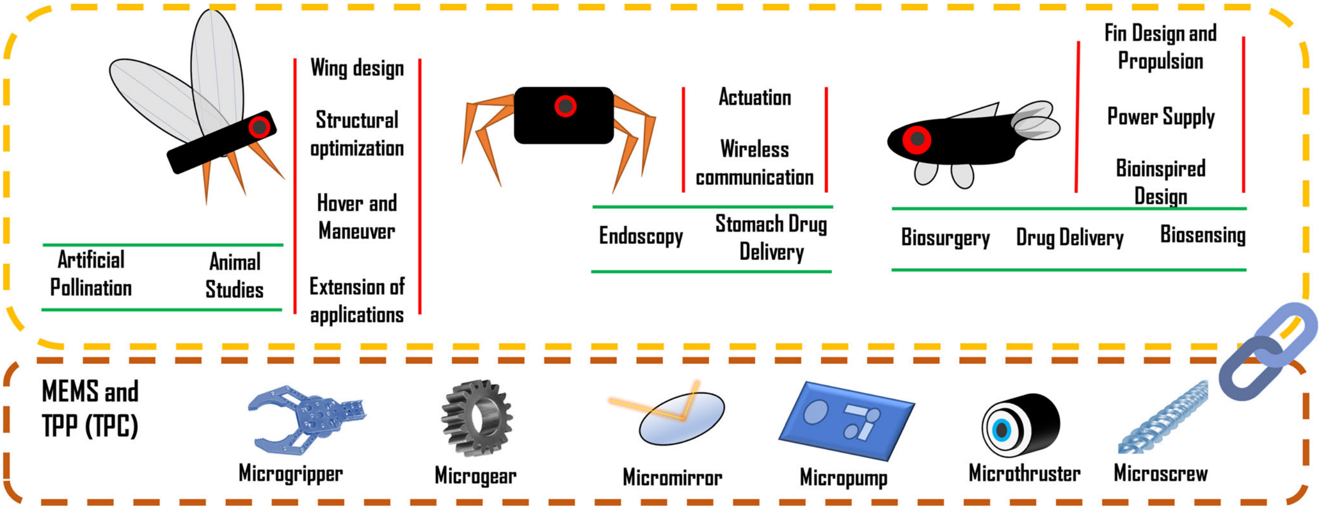

Fig. 2 Micro/Nano design and fabrication: building micro/nano robots in air (left), on ground (middle), and in fluids (right) is linked to MEMS or TPC technology through the need for micro/nano parts. Present challenges (red lines) and hot research topics (green lines) are shown in the top section. TPP stands for two-photon polymerization, which will be discussed in Section 5.2

Table 4 Recent FWMAVs articles to identify hot topics in the field

Feature(s)	Year	Ref.
Optimizing the wing shape based on pressure contours at different Reynolds number to enhance lift coefficient	2019	[97]
Use of strings in the wings of the vehicle to reduce weight	2019	[98]
Comparing flexural stiffness among different wing designs, inspired by *Manduca sexta* Forewings*	2017	[99]
Modeling of and a practical identification approach for flapping wing resonance frequency	2017	[100]
Gear and motor holder plate optimization for better efficiency and performance	2017	[101]
Complete design and control of a tailless FWMAV	2017	[103]
A five-step strategy to size the wing in flapping wing air vehicles	2017	[104]
Optimizing the wing design, surface area, aspect and taper ratios, and camber angle; based on experiments	2017	[106]
Hybrid wing design: making use of both fixed and flapping wings	2016	[107]
Mimicking and minimizing vein patterns on a wing based on dragonflies' wing models to facilitate fabrication*	2016	[108]
Making use of electro-adhesion to enable perching in an FAMAV	2016	[109]

**The first author of this review does not endorse animal/insect experiments*

- *Energy optimization*: Battery lifetime for wireless FWMAVs poses a challenge for long flights, demanding optimizations in wing design, choice of flight orbit, and structure. This has led to the creation of new ideas, such as choosing orbits with lower power consumptions during flight on limited battery [117], use of compliant wing hinges [118], and geometric and aerodynamic optimization of wings [119].
- *Extension of applications*: Animals, and in particular bees, pollinate about 70–90% of all crops [120]. Due to the unfortunate decline of bees, as a subsequent of human industrial activities, an idea in the recent years has been the development of robotic bees as crop pollinators. Yet, this idea has been rightfully criticized due to environmental and economic implications [121, 122], with the authors calling for actions to save the *real* bees. Besides artificial pollination, rescue mission, which is a classic use of robots, is also a subject of interest in paving the way for new applications of FWMAVs [104]. Inspecting excellent and exciting research on using robots to study natural lives of animals, the authors of this review propose using FWMAVs to conduct non-interventional research in the animal or insect kingdom. This would be similar to the intriguing research in [105], but at a different scale and with much less visiblity and interference.

3.3.2 On ground

Aside from micro, flying robots, the design of ground microrobots has been investigated. Actuation of mini-robots and making them untethered are two major challenges in this area, for which many solutions have been offered. As examples of early works in this area, utilization of a *giant magnetostrictive alloy*, as an actuator, was reported in a micro-robot in 1991 [123] and later a submillimeter robot capable of walking and carrying loads, equipped with thermal actuators, was introduced in 1999 [124]. Donald et al. designed and fabricated a MEMS robot that could be controlled to follow complex paths and steer without the need for any wired communication [125]. They used an electrostatic drive to actuate the device and electromechanical hysteresis to store information on the robot's body, and subsequently control its motion.

The idea of a wireless robot was also pursued by using a shape memory alloy (SMA, refer to Section 5) as a spring actuator in a wormlike mini-robot [126]. The communication was made with wireless signals, the power was fed to the robot by alkaline batteries, and pulsed magnetic fields were used for untethered actuation. Pawashe et al. showed the performance of a surface micro-robot with stick-slip motion that was actuated and controlled, again, by magnetic fields [127]. Its performance in air was observed to be the best probably due to the presence of a water lubrication layer, from humidity, that lessened the effect of friction. As it appears, the use of magnetic fields to actuate ground microrobots is dominant in the field. However, very recently, ultrasound actuation of microrobots has been reported by several research groups [128–130]. The propulsion principle is based on acoustic radiation force and steady bubble streaming, which leads to relatively high speeds. Such a robot is most suitable for monitoring or manipulating contents in the blood flow.

Inspiring applications of ground robots in general include endoscopy (by the use of a rolling microrobot) [131], drug delivery to the stomach (for a discussion of operating robots in acidic environments, refer to the end of Section 3.3.3) [132], and drilling for medical procedures in the vein or other tabular environments [133].

3.3.3 Inside water or other fluids

The next category of micro-robots are underwater vehicles, where effective usage of fins, maneuverability, and bio-inspired designs are desirable goals—just like in the FWMAV case. One might draw an analogy between fins in the former and wings in the latter, whose importance in the robot's performance is undeniable. Among the works focused on such robots, several mechanism designs can be identified after year 2000. A little back in time, it was in 2002 when Guo et al. used Ionic Conducting Polymer Film (ICPF) to make a fish-like micro-robot with a buoyancy adjuster to realize a three-degree-of-freedom motion [134]. In 2005, Deng et al. presented the fabrication and force measurement of fin-propelled micro-robot [135], and more recently, Wang et al. introduced a fish-like robot with a biomimetic fin and the ability to swim on a straight path and making turns [136].

Ye et al. used side fins, controlled by wireless communication, in addition to the rear fin to make a relatively large underwater robot [137]. Though they used a different scale from micro-robots, their use of pectoral fins and ionic polymer-metal composites (IPMCs) open the way for new ideas in the micro world, as seen in [72]. Besides mimicking the motion of fishes that predominantly use their fins to swim, robots inspired by other marine animals such as manta ray [138], lobster [139], jelly-fish [140], crawling organisms [141, 142] and multi-legged organisms [143, 144] are also presented in the literature. These can inspire new ideas for micro-swimmers as well.

One intriguing application of swimming micro-robots is their use in drug delivery, bio-surgery, and bio-sensing [145]. As propulsion in micron and nano-meter scale is a challenge, mainly due to space limitations, devising other propelling mechanisms is integral. Feng et al. have identified six main techniques to propel these small-scale robots [145], namely: irreversible strokes, oscillating bubbles, magnetic fields, biological mechanisms, active Brownian motor and self-thermophoresis, and chemical reaction. Some of these have already been discussed and some will be presented in the following.

In early 1990s, Ishihara et al. proposed a micro-robot, in the shape of a capsule for drug delivery, which was actuated and controlled by resonant ultrasound [146]. Later, Freitas made an effort to give a definition for an ideal drug delivery robot by listing its characteristics, which constitute being self-powered, being commuter-controllable, and having the ability to target individual cells with high accuracy in timing and transportation [147]. Such a robot might obtain its power from inner-body sources such as glucose or oxygen in the blood and rely on nano-pumps to deliver drug to the target. Other power sources for biomedical micro-robots include thermal harvesting via Seebeck effect inside the body, actuation using muscle cells, and wireless external sources such as induction and, as mentioned, magnetic fields [148]. Another example of a micro-robot actuated and controlled by magnetic fields was presented by Dogangil et al. for retinal drug delivery, otherwise requiring demanding microsurgery skills in a normal setting [149]. Between force- and torque-driven magnetic robots, the latter one is more favorable for nano- and micro-scale applications, in terms of propulsion efficiency [150]. Micro-pumps are also integral parts of drug-delivery robots and they can be mechanical—using electrostaticity, piezoelectricity, and SMAs—or non-mechanical—employing magnetohydrodynamics or electrowetting [151].

Besides power and delivery method, path planning is vital in small-scale robots so that they can approach the target (e.g., a cell), manipulate it [152] or inject a fluid inside it. To reach this goal for a micro-robot in the blood stream, a genetic algorithm was proposed for optimal planning and it was tested in a number of simulated environments [153]. It was to efficiently deliver a drug to an arbitrarily-shaped target with the least energy consumption, by minimizing the path length and turning angles.

Bio-inspired nano-robots intended for molecular injection or drug delivery are distinguished from the typical term "robot" by the fact that they do not necessarily have mechanical parts such as motors and gears. Rather, they can use biological/chemical sensing and a *lock-key* mechanism to load material into targeted cells or molecules.

For instance, Douglas et al. introduced a DNA nano-robot that could transport payloads to cells and deliver them after cell-surface sensing and reconfiguring its shape [154]. In addition, Ceylan et al. reported a 3D-printed helical micro-swimmer that is made of a biodegradable material and capable of swelling (in response to chemical activation) and releasing a theranostic cargo in the desired microenvironment [155]. In another intriguing application, the same research group also reported safe transportation of stem cells to target tissues using cell-carrying microbots, which are controlled by external magnetic fields [156]. Aside from externally controlled robots, the idea of nano-robots equipped with sensors and actuators using nano-electronics has also been proposed for different purposes [157]. Temperature, electromagnetic signatures, and specific chemical concentrations are among factors that are important in monitoring human body for the detection of diseases. Thus, they can be used for the design of novel electronic sensors.

As a comprehensive example of nano-robots, Cavalcanti and others outlined the architecture design of blood-borne nano-robots for medical target identifications [158]. They suggested CMOS-based sensors with nano-wires for the chemical, motion, and temperature sensors; CMOS and carbon nano-tubes (CNTs) for actuators, CMOS for power supply and active telemetry, and radio-frequency waves for data transmission. DNAs, for coupling energy transfer and protein for electrical discharge and ionic flux, were also discussed in their article. Their propositions nicely merge engineering and biological perspectives.

Moreover, Suraj et al. introduced a nano-robot for the treatment of coronary heart diseases[1] using Quantum Cellular Automata (QCA) [161]. During an artery clog, the pressure in the vein is higher than the normal values [162], and this difference can be sensed by piezoelectric nano-wires and it can actuate the nano-robots to travel to the clotted region [161]. In their study, quantum dots were selected for the nano-controlling action due to their low-power consumption as an alternative to CMOS circuits. As a more recent work, authors in [163] report an ultrasound-propelled nanorobot capable of removing toxins and bacteria. Light signals can also be used to actuate micro-swimmers [165] and such robots can be utilized in swarms as well [164].

When dealing with robots designed to operate in biological milieus, aside from technical concerns focused on the robots' functionality, biological considerations like the immune system's reaction to these external objects and barriers like seemingly impermeable tissues become important. Yasa et al. explored the interaction between three helical micro-swimmers with two types of white blood cells and showed that the morphology of bio-robots can play an important role in the immune response of the body to them. They further propose the use of macrophages within the design of personalized microbots for immunotherapeutic purposes [166].

As for biological barriers, Wu et al. investigate the possibility of penetration into the eye tissue [167] and Walker et al. consider the problem of penetration into viscoelastic mucin gels, which are part of boy's defense mechanism against pathogens [168]. The first group fabricate a magnetically-controlled microbot that can both overcome the penetration problem by a spherical head and a helical tail and the adhesion problem by a plant-derived coating. The second group take inspiration from certain bacteria that use the enzyme *urease* to overcome the harsh acidic environment of stomach and ease propulsion through the mucin gels. Based on this strategy, they built urease-coated microparticles that can be steered with magnetic fields through the viscoelastic mucus, opening opportunities for microbot development in gel-like and acidic environments.

4 Nano (micro) measurement engineering

The need to measure physical parameters such as force, position, velocity, acceleration, and temperature frequently arise in micro and nano systems. The use of different and novel materials for sensing will be discussed in more details in the next section. As will be seen, the development of new measurement systems usually overlaps with the invention or enhancement of novel sensors and actuators as some of their most integral parts, as recapitulated in Fig. 3.

Bioengineering applications, as mentioned in the preceding section, continue to attract the curious minds of researchers. In monitoring chemical and biochemical processes within such systems, temperature sensing with high precision can be important. Kehayias et al. used single atomic defects in diamonds as a sensing technique for nano-scale temperature measurements with sensors that can be as small as a few tens of nanometers [169]. These sensors are useful in chemical processes involving one or two molecules even in an ambient of high heterogeneity, e.g., a cell. The basis of such a sensing technique is the spin level change of the negatively charged nitrogen-vacancy inside a diamond as a result of optical excitement. The pace of the diamond response is guaranteed by diamond's very high conductivity.

Another method for sensing temperature in the nano-world is making use of CNTs. The resistance of these tubes is linearly sensitive to temperature and that makes them a good candidate for temperature sensors. Kuo et al. grew CNTs between two electrodes using MEMS techniques and showed that the resistance of a CNT exhibits a highly linear relationship with temperature [170].

Needless to say, atomic force microscopy (AFM) has a wide range of applications for force measurement in micro and nano environments. Since, with high probability, the reader is familiar with this well-known method; here, only some of its most recent applications are discussed. A case in point is the effort made to measure adhesion force, which is essential in the interaction between particles in nano scale. Authors in [171], offer a systematic methodology to measure adhesion, based on probability theory, and a solution to avoid errors caused by force measurement. Similarly, authors of [172] studied adhesion reduction when water changes form from planar into curved, and suggested some applications for their findings, namely design of nano-biomaterials by surface-tension control.

On top of AFM, several novel force measuring techniques have been proposed, including making use of capacitance sensors, with resolutions down to 0.11 nN [173], and upconverting specific nanoparticles, which creates a way to visualize force and its value, by the color of the light emitted during the upconversion process [174].

One application that has gathered attention during the last years is submillimeter rheology, or the study of viscoelastic

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[1] Coronary heart diseases can be effectively prevented, even reversed, with a change in lifestyle, as shown ingeniously by Dr. Esselstyn and others [159, 160]. Thus, the need for advanced treatment methods is not authentic when there are simple ways to prevent and reverse the disease [first author].

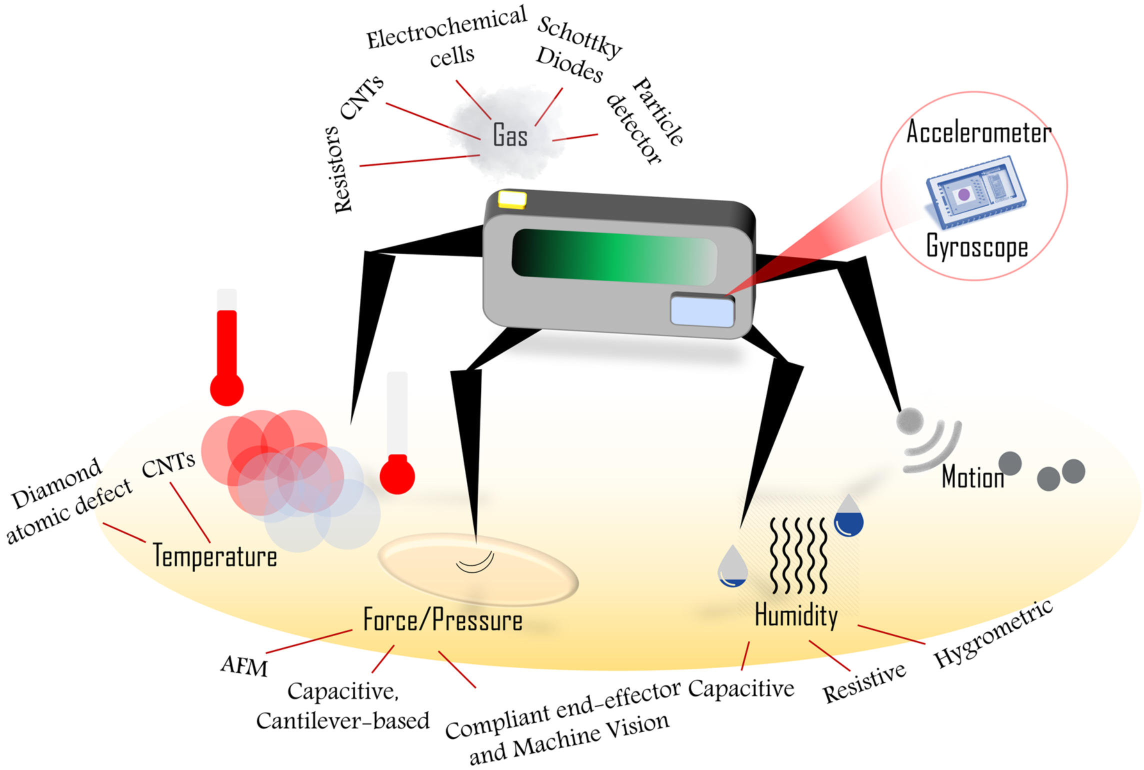

Fig. 3 Measuring various parameters is crucial in a micro/nano mechatronics system. Measurements are closely tied with the development of new materials for sensing

properties of soft media by observing minute trace particles [175]. Recently, Garcia et al. used piezoelectric actuators, interferometric displacement sensors, and a flexure hinge, as a force sensor, to develop a micro/nano-rheometer, capable of making viscoelastic, boundary slippage, and elastohydrodynamic measurements [176]. Other applications include velocity measurements using stereoscopic micro particle image velocimetry (micro-PIV), particle tracking velocimetry (PTV) [177] and contact-type scanning devices for micro/nano coordinate measuring machines [178].

Aside from sensors that have been developed to measure specific variables, there are works that concentrate on elevating the precision and accuracy of the measurement. Enhancing the accuracy of a measuring system could take several steps. As an example, in a coordinate measuring machine (CMM), Fan et al. made novel changes in the conventional design to increase precision: replacing the rectangular bridge that holds the Z-axis probe with an arced bridge, designing a co-planar XY stage to reduce the Abbe error, employing ultrasonic piezo motors for all directions, and using LDGI (as introduced in Subsection 2.2.1) for position feedback [179].

Measuring the derivatives of space coordinates in the submillimeter world is a necessity as well. Using a nano-optic sensor equipped with nano-gratings to modulate the polarization and intensity of an incident light source, Krishnamoorthy et al. presented an accelerometer with nano-g (9.8×10^{-9} m/s^2) measurement capability and low thermal noise [180]. To measure such small accelerations, mass displacements of femto-meter scale and low resonant frequencies are needed, and that requires large mass and weak spring constants. Thereby, the authors used surface and bulk micromachining to enable such mass-spring combination. The difference between the thermal expansion coefficients of the MEMS device and the substrate created thermally-induced stress in the mass dynamics. Therefore, the proof mass was isolated using a gimbal around it with springs that filtered the mentioned disturbing effects.

Achieving high sensitivity and noise resistance are two important challenges in measuring acceleration in MEMS. To improve these, authors in [181] developed a highly sensitive MEMS accelerometer for micro-seismic events and detection of low frequencies, by comb-drives of different functions and a closed-loop control scheme. Similarly, optimized mechanical structures (micro levers, resonance, and proof mass) and oscillator circuits accomplish the above goals [182].

Design of new MEMS gyroscopes are also being investigated, mostly aimed at bandwidth tuning, high resolution measurements, and zero drift. Making use of the relationship between residual quadrature and drive signals, as well as a force-feedback controller, the authors achieved mode-matching in resonance and the ability to tune operational bandwidth [183]. To reduce drift, correction of coupling stiffness to mitigate quadrature error in a dual-mass gyroscope [184] and the use of adaptive Kalman filter [185] have been proposed. When temperature variations cause drift, utilization of temperature sensors to compensate the error is accompanied with lag. Thus, maintaining stability and repeatability at high resolutions (down to 1 ppm) becomes formidable. Instead, making use of temperature dependence on drive-mode resonant frequency of a quadruple-mass gyroscope, as suggested in [186], leads to a self-sensing gyroscope that can self-compensate drift.

Applications of MEMS gyroscopes are expansive, including their use in FWMAVs for stabilizing hover height [187] and controlling fast-steer micromirrors [188]. Other sensing mechanisms developed to measure physical parameters, like motion and humidity in submillimeter scale, include graphene resistance-based strain sensors, made by micro-scale meshes, to monitor human motion such as blinking, speaking (the vibration of the throat), and breathing [189]; and using piezotronic effect—applying strain on the material to tune the Schottky barrier height—to enhance the performance of a zinc-oxide humidity sensor [190].

5 Nano (micro) materials for sensing and actuation

New materials have been investigated in the last few years for sensing applications such as in gas and humidity sensors and actuators that are required in nano and micro environments. The invention of new materials could be due to a need for higher sensitivity, function in certain environments (e.g., within body), or possession of specific, desirable features useful in actuation or sensing. Development of new materials for gas and humidity sensors, as well as sensing in biological environments, is very much active in the scientific community. Therefore, two subsections are allocated to them.

5.1 New materials and methods in gas and humidity sensors

Gas sensors, with high sensitivities, are still being explored and actively enhanced, majorly for the detection of hazardous chemicals or monitoring. In micro and nano scales, several sensing principles can be identified in the literature [191]. These include electro-chemical cells using materials such as functionalized graphene oxide [192], resistors using ultrathin vanadyl-phthalocyanine [193], ion mobility using MEMS particle detectors [194], Schottky Diodes using a heterojunction of nanohybrid materials [195], and CNTs [196]. Among the works in the recent years, one can observe that increasing sensitivity and identification of certain gases—like ammonia [197] and formaldehyde [197]—are being actively investigated. To achieve higher sensitivities, adding gold nanoparticles to a single nanofiber of TiO_2 [198] and wrapping CNTs in polymers [199] have been reported in recent years.

Certainly, gas sensors can be integrated in small-scale mechatronic systems to create new opportunities. As an example, authors in [200] equipped a micro-drone with a metal-oxide semiconductor gas sensor to map gas distribution in a 3D space. More interestingly, others have utilized a solid-state gas sensor on a nano quadcopter to localize the source of an odor at indoor spaces [201].

Humidity sensors are also important for environmental monitoring, personal safety, and industrial control. These operate based on various principles with different materials. These include (1) *Capacitive* sensors including thin layers of gold/gold nano-compounds [202] or ceramics [203], porous silicon [204], and polymers [205]; (2) *resistive* sensors making use of ceramics [206], electrolytes [207], and polymers [208]; and (3) *hygrometric* sensors using a Si or SiO_2 membrane with a layer of polyimide on top [209]; or taking advantage of a thin layer of aluminum oxide [210].

Typically, organic polymer films and metal-oxide nanoparticles are used for humidity sensing; however, these materials are reported to possess weak chemical stability and low mechanical strength. Lei et al. employed electroplating to generate one-dimensional nano-fibers that are uniform in diameter and long in length; and can compensate for the drawbacks of typical humidity micro-sensors [211]. The principle behind the sensing capability of these nano-fibers is their impedance alteration as a response to humidity change.

One fascinating use of humidity-sensitive nano-fibers is to propel a micro-robot by the humidity-induced tension in the fiber structure [212].

5.2 New materials in Nano (micro) biological sensors and actuators

Materials compatible with a biological ambient, such as nano-composite polymers and shape memory materials, due to their wide biomedical applications, have attracted much interest recently. Given the development of microrobots designed for biomanipulation [213], one can imagine what important role new material can play in the field of submillimeter mechatronics.

As briefly noted, biodegradability of micro-robots is also a crucial feature for many applications, as in the case of cargo-delivery microbots in [155], which swell and release their cargo in response to a specific chemical. Similarly, biodegradable, magnetic micro-scaffolds composed of a porous surface, which can support various types of chemicals and cells, have been proposed for in vitro manipulation and in vivo cargo delivery [214]. For many magnetic particles can be toxic to living tissues, Kim et al. have proposed the retrieval of these particles from the site of delivery, as a practical solution, so that they do not remain in the body [215]. Biocompatible solutions like these ensure that the microbot components do not harm biological media.

Sensing is also closely linked with detection applications. Biological detection is essential in the early detection of diseases, with the aim of minimizing false-positive and false-negative results. One approach to detecting biological matter is chemically labeling proteins with quantum dots, florescent and radioactive agents, or enzymes. Then, bioassays are used to detect a group of certain molecules with high specificity. As two examples, magnetic labeling [216]—a non-invasive and physically and chemically stable method—and nanoparticle-based labeling [217] have been used for protein separation and analyzing DNA, respectively.

The other approach is label-free detection. Calorimetry, nanowire and nanotube-based transistors, quartz crystal oscillators, and surface plasmon resonance (SPR) belong to this category of detection. In this technique, the detection coincides with a change in the mechanical, electrical or other properties of the materials. One of the recent label-free detection methods is using an electronic aptamer-based (E-AB) sensor, which generates a signal as it binds with a target [218]. This type of sensor has been employed for detecting cocaine in blood, saliva, and adulterated samples [219] and small molecules, such as adenosine [220]; vitamins and antibiotics; and organic dyes, protein, cells, and microorganisms like bacteria [221].

CNTs, which were previously mentioned for gas and temperature sensing, are especially fitting to sense biological particles. They have been used in biosensing of materials such as glucose [222]; and silicon nanowires, utilized in the detection of MiRNAs [223] and DNA hybridization [224]. Barone et al. synthesized and tested single-walled CNTs for the purpose of near-infrared sensing [225]. They showed that these CNTs modulate their infrared emission in response to adhesion of specific molecules. Their analysis revealed that two possible mechanisms, *charge transfer* and *fluorescence*, can be used for signal transduction. This capability of single-walled CNTs have been used in the detection of DNA hybridization [226] and DNA conformational polymorphism [227].

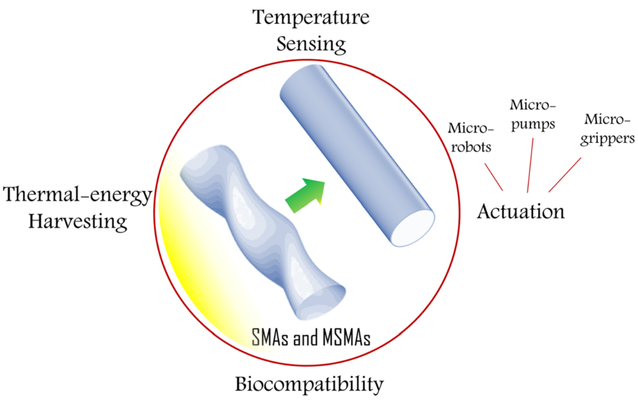

Fig. 4 SMAs and MSMAs have various applications in actuation and sensing in micro−/nano-scale systems

Besides CNTs, organic conducting nano polymers and nanocomposites have found their way in biosensors [228, 229]. These materials are suitable for sensing a variety of analytes, such as histidine-tagged proteins [230] and cancer antigen biomarkers [231]. Conducting polymers (CPs) have distinct electrical, optical, and mechanical properties and due to their conjugated-electron system, they have attractive physical and chemical features [232].

CPs are typically used for electrochemical sensors, where the interaction between CPs and certain analytes can be quantified and measured. Detecting toxic gases and volatile organic matter are among other applications of these sensors. For a liquid environment, where, unlike a gas environment, adhesion is a difficulty; modified PPy nano-tubes have been introduced to immobilize the CPs [232]. In the future, these nanomaterials are anticipated to have high reliability, high sensitivity, flexibility, and multi-analyte determination ability.

Other types of polymers have been proposed for micro and nano systems as well. For example, Tung et al. fabricated a functional epoxy-based (SU-8) microrobot—as a cheaper alternative to a gold-based one—that moves relatively fast on a 2D surface (20 mm/s) and can carry loads while being controlled by a magnetic field [234]. The advantage of using polymers in micro or nano robots is that they enable the use of conventional MEMS-based fabrication techniques as well as novel techniques such as two-photon polymerization (TPP) lithography, which enables resolutions smaller than 100 nm, suitable for nano-robotic applications [233]. TPP is a voxel-by-voxel approach that uses direct laser writing to create solid components. When materials like hydrogel, photo-crosslinkable proteins, and water-soluble photo initiators are used as the base for the polymerization process, biocompatible components can be created to be used for biomedical applications.

In addition to the materials introduced, shape memory materials, particularly SMAs and MSMAs, also have great potential in biomedical sensing besides many other applications. Pseudo-elastic and shape memory effect are the two major properties of SMAs, specifically nickel-titanium (Ni-Ti) alloys, that ascertain reverting to the original form, even after large mechanically- or thermally-induced deformations [235]. At low temperatures, heat can retrieve the shape of an SMA prior to the deformation, and at high temperatures, an SMA can be reversibly elongated up to 10% of its initial length, a behavior named *super-elasticity*. Transformation between austenite and martensite phases is the mechanism behind such properties. In uniaxial loading two forms of martensite, M^+ and M^- and an austenite form appear [236].

Among different SMAs, Ni-Ti alloy is particularly attractive in the biomedical field due to its favorable characteristics: biocompatibility [237], computer tomography compatibility

[235], and tissue-like behavior [238]. SMAs can be used for different sets of applications based on their working principle; they can be used to create displacement, stress, or force, or to store potential energy [239]. They have been used to build micro-actuators for diverse purposes. Zakharov et al. built a thermally-controlled actuator using SMAs to manipulate nano- and micro-sized objects such as CNTs [240]. The micro-actuator was of cantilever type, made up of TiNiCu, and controlled by a temperature difference of only 20 C. The authors expanded the application of such actuators to micro-surgery with the aim of organ damage minimization.

As another interesting application, Caizzone et al. utilized Ni-Ti on a radiofrequency identification antenna to detect temperature thresholds in a wireless manner [241]. When the SMA senses the temperature, it acts as a switch for the antenna to activate microchips according to the temperature of the object of interest, whether cold or hot. Such application of SMAs can be used in micro-devices as well. Thermal actuation of SMAs was reported in micro devices such as micro-pumps [242], micro-grippers [243], and micro-robots [136, 244].

In addition, Magnetic SMAs (MSMAs), members of the Heusler materials class, have considerable magneto-crystalline anisotropy, which results in magnetic moments to orient in energetically preferred directions [245]. These materials can transform under a first-order martensitic phase and consequently exhibit sudden and large changes in their magnetic and mechanical properties [245].

The basic principle behind MSMAs, as their name hints, is the reorientation of martensite due to magnetic stimulation. Magnetization also changes because of the strain inside the material, leading to a variety of sensing opportunities like micro-actuation [245] and fast magnetic-field sensing [246]. A rather newly-investigated phenomenon in these materials is *thermomagnetism*, which has been implemented in actuators [247] and thermal energy harvesting systems [248].

As a multifaceted example in the micro world, involving the science of both materials and control, Riccardi et al. employed an MSMA actuator for precise micrometer positioning [249]. The elongation was actuated directly by magnetic inducement and contraction was made possible by a spring, applying a force in the direction opposite to elongation. Since the MSMA had a low permeability, leading to a high inductance in the excitation, the cut-off frequency was limited. This made hysteresis compensation a necessity, and thus the authors employed Preisach-like Krasnosel'skii–Pokrovskii model to control it. Figure 4 summarizes some of the applications of SMAs and MSMAs discussed in the preceding paragraphs.

Multifunctionality and multi-stimuli responsiveness using smart, soft materials are among the recent research ideas in sensing and actuation, especially for micro and nano robots operating in biological environments. These features are essential because the biological world is replete with uncertainties and varying conditions that require adaptive behavior. In their novel paper, Huang et al. report a nature-inspired microrobot that is not only controllable by magnetic fields but also capable of changing its morphology in reaction to near-infrared laser heating [250]. By a set of nano particles whose alignment can be reconfigured, the authors have been able to create a microbot with various magnetic axes, enhancing motility in different conditions. In a similar attempt, authors in [251] use a temperature-sensitive material (pNIPAM) along with a pH- and ion-responsive material (acrylic acid) to create magnetically-controlled micro-rollers and micro-screws that change their size in response to variations in temperature, pH and ion concentration. These advances pave the way for the fabrication of highly capable and programmable microbots for biomedical applications.

As mentioned in Subsection 3.3.3, development of materials and coatings for nano or micro robots that can interact well with the body's immune system and pass through biological barriers like certain tissues and gel-like or acidic environments is also an active topic within the field.

6 Conclusions

This brief, holistic review clearly reveals the interconnection of different categories of nano/micro mechatronic systems, namely control engineering and modeling, design and fabrication, measurement engineering, and materials. Unique opportunities arise from this holistic observation, like a gas-sensor-equipped [201] or a nano-fiber-activated microrobot [212], which are born out of the integration of all four categories. One might argue that some of the sensors discussed in this review do not directly fit into the topic of mechatronics or robotic; yet, if novel biological nanobots are considered, the importance of such sensors become clear in future research. For example, one can imagine how the ultrasound-propelled micro-robot in [130] can be equipped with several material-based sensors to monitor blood parameters or detect analytes to diagnose disease.

Figure 5 encapsulates this holistic view upon minute mechatronic systems and depicts some of the overlapping areas. Looking at the nano/micro mechatronic systems in its entirety, one can make the following observations:

- These systems may be classified as (a) the ones that operate on nano/micro scales, like nanopositioners or atomic force microscopes and (b) the ones that not only operate in nano/micro scale, but also are nano−/micro-sized themselves, like FMAVs, SMA or hydrogel microrobots. In Group (a), control engineering and design and fabrication are the paramount fields for current research, while in Group (b), in addition to those two fields, measurement

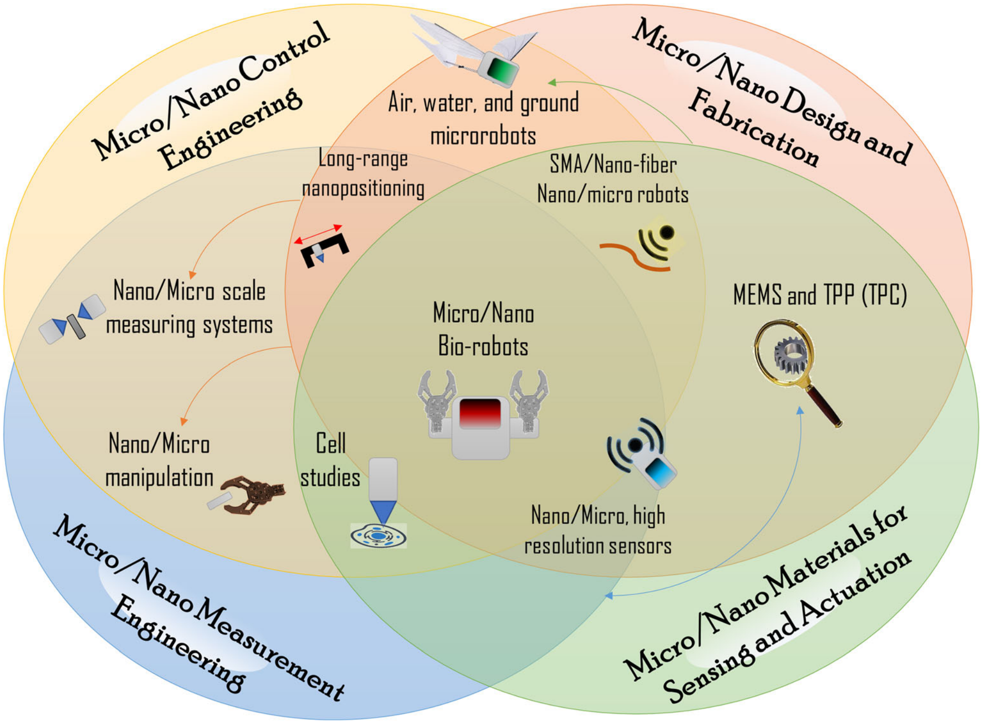

Fig. 5 A holistic view of micro/nano mechatronic systems with recent applications

techniques and new materials for sensing and actuation are essential and continually being investigated. Receiving feedback from small-sized robots that operate within the body is a live challenge and potential solutions could transform in vivo robot control and performance.

- Nanopositioners and nanomanipulators have reached a mature state; yet, the control of friction, resonance, and hysteresis still pose challenges for researchers. Research in these areas could be also useful in the control of robots that are steered using external fields.
- As a particular field that interconnects all the four categories considered in this review, nano/micro robotics is finding applications in the biological and biomedical world at a fast pace. Drug delivery, tissue monitoring, cell manipulation, and micro-surgeries are among active research topics in this area.
- Design and fabrication become especially important in novel MEMS techniques and TPP (TPC) as well as in the construction of micro/nanobots. These robots can operate in air, on ground, or in water (fluids) and enhancing them in terms of performance and applications cannot be imagined without the incessant progress in the mentioned fabrication technologies.
- Measurements and sensing are closely interlinked and advancements in the latter, as well as research on new materials, contribute significantly to the former. Yet, measurement systems are also progressing on their own; with clear examples seen in improving the accuracy of CMMs and micro-gyroscopes. Research on materials is also expanding for actuation purposes, independently from measurements, leading to a new class of microrobots that operate with novel materials, such as SMAs or humidity-sensitive nano-fibers.

Alongside the above perspectives, it is hoped that the identified challenges, such as controlling FWMAVs, friction control, and opportunities like using microrobots to study animal behavior, in a non-interferential manner, instigate new research projects in near future.

Moreover, as clearly seen in this review, research in the field of biological micro and nano robotics is on the rise and many obstacles that seemed impossible to surmount are now being broken. One of the these barriers that still exists to some degree seems to be a gap between research into these robots from purely engineering and purely biological views. As these two fields are merging in the scope of multidisciplinary research, one can expect to see highly capable micro and nano robots very soon that go beyond many classical definitions within the field of robotics. These robots are predicted to be multifunctional, multi-stimuli responsive, shape-shifting, biodegradable or biocompatible, propelled by chemicals or other sources of energy within bioligical media, equipped with several sensors to monitor conditions, capable of transmitting a form of feedback signal to the outside world, compatible with the immune system, and able to pass biological barrirers. While biodegradable robots are suitable for treatment purposes, long-lasting immune-system- and bio-compatible robots could create outstanding opportunities for monitoring and diagnostic purposes—one can imagine robots being able to diagnose cancer, Alzheimer's or schematic heart disease in their earliest stages.

Meanwhile, research in design and control of micro and nano positioning and manipulation systems can contribute meaningfully to the precision control of these submilimter robots and careful investigation into the features of external waves—whether optical, magnetic, or ultrasonic—could generate various modes of action for them. One thing that is for sure is that, to achieve these far-reaching goals, a close cooperation among all these engineering and scientific disiplines will be inevitable.

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Data availability Not applicable.

Code availability Not applicable.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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