An Overview of Microrobotic Systems for Microforce Sensing

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Abstract

Considering microbotics, microforce sensing, their working environment, and their control architecture together, microrobotic force-sensing systems provide the potential to outperform traditional stand-alone approaches. Microrobotics is a unique way for humans to control interactions between a robot and micrometer size samples by enabling the control of speeds, dynamics, approach angles, and localization of the contact in a highly versatile manner. Many highly integrated microforce sensors attempt to measure forces occurring during these interactions. However, they are highly difficult to predict because the forces strongly depend on many environmental and system parameters. This article discusses state-of-the-art microrobotic systems for microforce sensing, considering all these factors. It starts with presenting the basic principles of microrobotic micro-force sensing, robotics, and control. It discusses the importance of microforce sensor calibration and active microforce sensing techniques. Finally, an overview of microrobotic microforce sensing systems and applications are discussed, considering both tethered and untethered micro-robotic approaches.

Contents

1. Introduction

For 30 years, microrobotics has been considered a scientific field in its own since it provides original tools and methods able to achieve tasks at the micrometer scale. This scale is characterized by objects of interest with at least one dimension of less than one millimeter, which not only limits manual intervention by a human operator but is also the subject of numerous application requirements. In this scope, microrobotics first appears as a unique and novel ability for humans to interact with microscale objects. These interactions appear to be highly useful for the purpose of characterization and control for manipulation and assembly tasks. Many robots have been developed and bring the ability to set several key parameters of this interaction (Fig. 1). Controlling the interaction between a robot and its environment, e.g. biological objects, synthetic components, tissues, etc., generally referred to as "samples", remains at the same time an open question and also central to the success of most tasks. In fact, the problem of controlling these interactions deals with several interrelated issues specific to the microscale as shown in Table 1.

In this context, force sensing has emerged as a key technology to measure forces occurring between a robot and a sample. Even though macro-scale force sensing has been a widely studied and developed field, their methods cannot be directly applied to microscale applications. Many of the constraints in microforce sensing stem from the reduced size scale and high-resolution requirements. Other important considerations depending on the force sensing methods may include possible microfabrication difficulties, sensor noise, or temperature and electrostatic effects. Some of the main challenges associated with microforce sensing are due to the small footprints required and difficult fabrication procedures. Additionally, the signal to noise ratio can be poor for some sensor types and, oftentimes, is highly dependent on environmental conditions. Despite these challenges, many microforce sensors have been designed by researchers as demonstrated by several survey papers (1, 2, 3, 4, 5). Also, a few companies have brought microforce sensors to the market: FemtoTools (CH), TEI (FR), THK Precision (JP), Honeywell (US), Kleindiek (DE), Bruker (US), and CLA (CH). The effective use of force sensors for microscale applications is however not straightforward, and presents several challenges. First, microforce sensing cannot be carried out directly and requires deforming a force sensing body (Fig. 1 (a)). Micropositioning robots are generally used to control the position, speed, acceleration and relative angles of the sensor body before and after the contact with the sample. The robot is thus a critical part of the measurement chain and highly influences and dictates the efficiency of

Microfabrication: Set of manufacturing techniques used to produce devices with structures at the micrometer scale and below

Microforce sensors: Sensors able to measure forces acting at the microNewton scale

Microscale applications: Applications involving objects or components at the micrometer scale

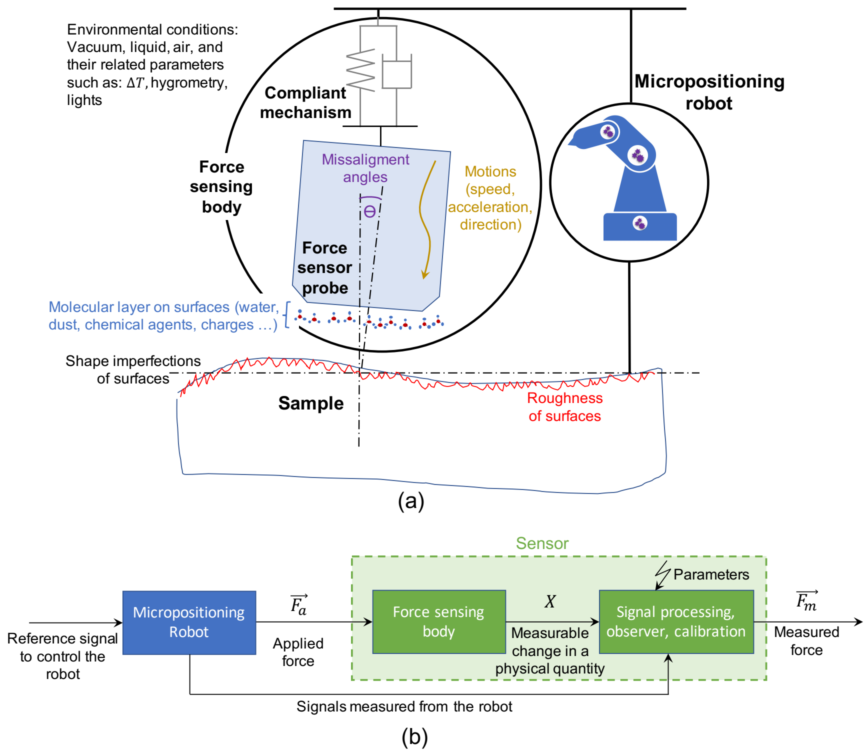

Figure 1

(a) Influential parameters for microforce sensing with robots. (b) Principle scheme for microforce sensing with robots. A micropositioning robot generates a relative motion between the force sensor probe and a microscale sample inducing a force ($\overrightarrow{F_a}$) to be measured ($\overrightarrow{F_m}$).

the force measurement. For instance, it can compensate for misalignment, drift and other measurement system uncertainties. Hence, most of the time microforce sensing cannot be done when considering the sensor alone and requires the consideration of the micropositioning robot. Second, the force sensing body when being deformed by the robot, provides a measurable change in a physical quantity such as strain or displacement. This change is used to provide the measured force ($\overrightarrow{F_m}$) which is an estimate of the force applied by the robot ($\overrightarrow{F_a}$), as shown in Fig. 1 (b). To obtain microforce sensing that matches applications requirements, the range, resolution, bandwidth, but also its accuracy directly depend on the way this estimation is done. Dynamic modelling of the force-sensing body, automatic control methods, data processing, as well as sensor calibration, also have to be considered in the process of microforce sensing. With these aspects in mind, this article presents the state of the art in microforce sensing, where the microforce sensor, the microrobotic system, the control and signal processing are included in a complete measurement chain operating in a specific environment (Fig. 1).

Micropositioning robots: Robots having at least 3 Degrees of Freedom able to achieve positioning tasks at the micrometer scale

In this paper, Sect. 2 will present some of the fundamentals of microforce sensors, including their performances and the physical principles on which they are based. Sect. 3 deals with an overall picture of robotic issues for force generation and sensing as well as

Table 1 Main challenges of microforce measurement at the microscale.

Microscale characteristics	Consequences for microforce sensing
Local physical effects (electrostatic, surface force predominance, etc.)	- Fast motion occurs around the contact between the sample and force sensing body (pull-in and/or pull-off effects) - Unwanted relative motions between sample and force sensor body
Environmental parameters, such as temperature and humidity	- Drift of the measurements, increase in standard deviation, loss of measurement traceability
Imperfect motions generated by the robot (non-linear actuation, geometrical imperfections, backlash, closed-loop induced delays)	- Introduction of additional influential parameters to the measurement - Increase in standard deviation - More complex analysis of influential parameters
Compliance of the measuring instrument on the same order of sample	- Difficulty in separating the properties of the sample from those of the instrument
High dynamics of objects	- Unwanted and/or uncontrolled vibrations - Sensor noise - High bandwidth in measurement and control

the associated control strategies. Sect. 4 is dedicated to microforce sensors calibration issues. Sect. 5 introduces active sensing which is a specific case where actuation and control play a fundamental role in force sensing performance. Sect. 6 introduces state-of-the-art microrobotic systems used for microforce sensing and the main applications. Finally, some conclusions are presented in the last section.

2. Microforce sensing: main principles and methods

Despite the challenges related to microforce sensing, multiple types of sensors have been used to achieve μN-level force measurement, each with their own advantages and disadvantages, as will be discussed in this section. They include vision-based, capacitive, piezoresistive, piezoelectric, optical, and field based force sensing techniques, among others. The goal of this section is to focus on the most popular methods employed for microforce sensing and possible integration with microrobots. To compare different microforce sensing methods, several key sensor properties such as resolution, range, trueness, among others need to be properly defined. In this review, **resolution** is defined as the smallest change in measured force detected by the sensor in question, while the **range** is defined as the latitude of forces in which the sensor can reliably measure them. Lastly, the **trueness** of a sensor refers to how accurate it is, in other words, how close the measured value relates to the actual force. As will be discussed further in this section, there are many challenges in microforce sensing, and one of them is the lack of a standardized definition for all these terms and a concrete way to compare different sensors. Using the definitions above, different types of microforce sensors will be contrasted, highlighting their specific advantages and disadvantages. Other considerations that must be taken into account when comparing different force sensing methods are their sensitivity to environmental conditions (temperature, humidity), measurement noise susceptibility, frequency response of the measurement, and complexity

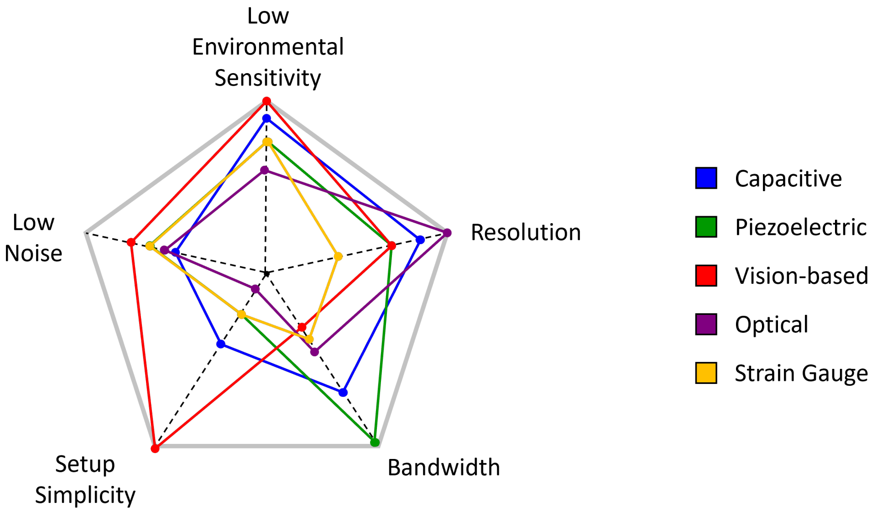

Figure 2

Schematic comparing different working mechanisms of commonly used force sensors for microscale measurements and below. Note: points farther away from the center denote better characteristics in that specific metric.

of the required experimental setup (circuitry, overall footprint, necessary filters). Fig. 2 shows a comparison of the methods described in more detail while Fig. 3 provides the range to resolution representation of microforce sensors available. This figure shows that commercial sensors are widely used for measurement ranges greater than 10 mN, between 100 μN and 10 mN numerous sensors are proposed by researchers with strong challenges around the measurement range/resolution ratio as well as the number of measurement axes, and finally, very few solutions allow measurement ranges below 100 μN.

Capacitive force sensors work by measuring the change in capacitance in the device, which can be directly linked to an applied force. In the simplest capacitive sensors, a set of conductive parallel plates insulated from each other, usually with a dielectric material between them, is used as the main sensing body. Therefore, when a force is applied to the system, these parallel plates move relative to each other. This results in a change of mutual capacitance, which is measured, and the applied force computed from it. This same effect is utilized in modern accelerometers, which use parallel plates attached to a proof mass system. This type of force sensor is extremely popular (12, 41, 9) since it can measure forces in a wide range, from mN to the pN range. Additionally, it also provides a good frequency response, is not very sensitive to environment changes (such as humidity and temperature), and requires very low energy to operate. On the other hand, capacitive force sensors are highly susceptible to noise, often requiring complicated circuitry for normal operation and to filter out the noise. This can result slightly larger footprints that can prove hard to integrate into other microsystems.

Strain gauge forces sensors are another very common approach for sensing. As force is applied to the sensor's structure, deformations will occur according to Hooke's law, resulting in a change of resistance, enabling the applied force to be calculated. We can distinguish two

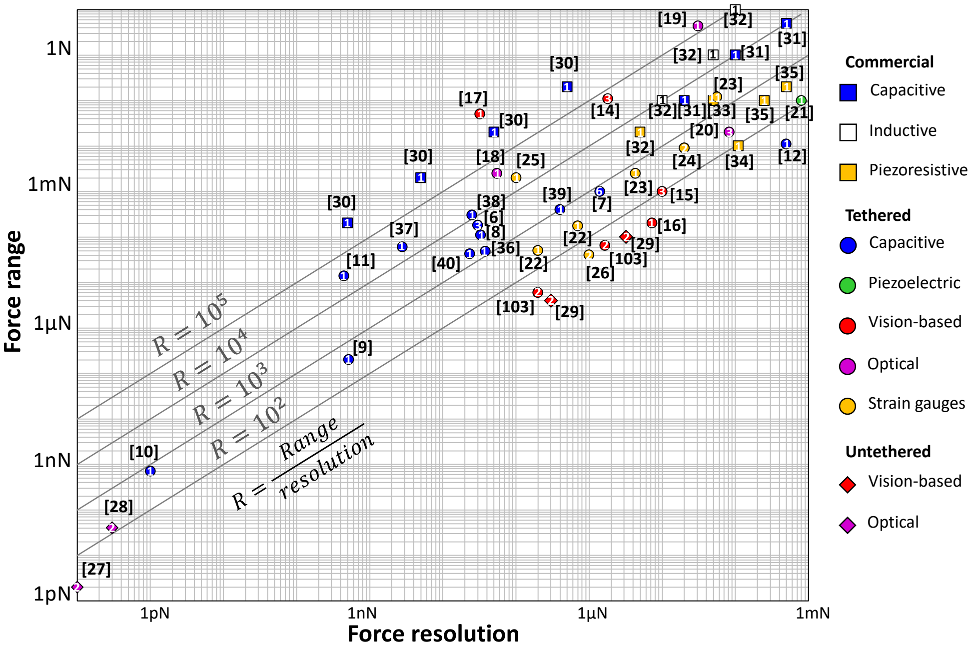

Figure 3

Microforce sensors available commercially or in the literature: range versus resolution plot along their working principle. Numbers inside the different shapes refer to the number of measurement axes and R is the Range to resolution ratio. These performances usually consider the sensor and its signal conditioning unit associated with its signal processing unit for commercially available sensors while only the sensor with its signal conditioning alone for sensors in the literature.

Tethered robots: Robots whose base and tip (end-effector) are physically attached by a tether

Untethered robots: Robots whose base and tip (end-effector) are not physically attached. The end-effector is moved using external fields that act at a distance, such as magnetic fields

sub-groups: metallic and piezoresistive strain gauges. The metallic ones exhibit a change of resistance according the strain mainly because a geometrical modification (elongation, contraction). On the other hand, piezoresistive sensors utilize a change of the resistivity of the material (piezoresistive effect) to compute forces. The gauge factor (G) is a metric that corresponds to the ability of the material to have a change in resistance (ΔR) based on its deformation (ε). This factor is defined as $G = \Delta R/(R.\varepsilon)$. Metallic strain gauges allow a gauge factor from 2 up to ≈5 for platinum. Piezoresistive strain gauges offer greater gauge factors from around 20 for poly-silicon up to 100-200 for silicon according the doping concentration and P or N type material.

Metallic strain gauge forces sensors are very popular due to its simplicity and low cost (42, 43). Additionally, it provides a sensing range around the mN-level and it has been deeply studied. These sensors can also be susceptible to environmental conditions (temperature, humidity), can present elevated noise levels and need a Wheatstone bridge to amplify the quite small resistance changes and, at the same time, amplify the noise too. Piezoresistive strain gauge sensors (44, 24) are also widespread for force sensing, since they have a relatively simple working principle. However, they need specific clean room facilities for fabrication, making them more complex to fabricate and usually more expensive. Thanks to their larger gauge factor, piezoresistive strain gauges have a wider sensing range, usually around the mN to sub-mN level. Similarly to metallic sensors, piezoresistive gauges also typically require a Wheatstone bridge, however, a lower amplification gain is needed, resulting in more favorable signal-to-noise ratio and expected stroke and resolution. As the piezoresistivity can be considered as instantaneous effect, the dynamic performance of such a sensor is directly linked to dynamic capability of the compliant mechanism (deformation body) of the sensor that integrate the gauges. Despite these benefits, this kind of sensor still faces some issues when it comes to miniaturization of its footprint and attachment to different test beds. Furthermore, some materials that present the piezoresistive effect, like silicon, can be extremely brittle, making some force measurements difficult.

Piezoelectric sensors are able to compute applied forces by measuring the electrical charge changes that occur due to mechanical deformation, a property of the direct piezoelectric effect (21, 45). The most attractive feature of these sensors is its high frequency response, making it the optimal solution for measuring microdynamic systems. Furthermore, piezoelectric sensors are usually small, have high sensitivity, and have a relatively simple structure. However, these sensors are unable to measure static forces, cannot operate in high temperatures, and charge leakages can occur, resulting in some measurement drift over time and lower reliability.

Optical technology has been used in multiple different ways to achieve microforce sensing (46, 47, 48, 49), such as a laser Raman spectroscopy techniques and a laser interferometer method, among others. One notable optical force sensing technique is the use of optical tweezers for measurement. Here, a focused light beam creates an optical trap in which a force is always exerted on the trapped particle towards the center of the beam. When an external force is applied to the particle, its position will deviate from the center of the optical trap, enabling the calculation of the exerted force based on this deviation. Utilizing this sensing method, a wide sensing range in the pN-level is possible, but large costs are usually associated with it and there are limitations regarding the types of particles that can be used for force sensing.

In contrast to optical-based microforce sensors, vision-based sensors utilize images taken at different times along with a computer vision algorithm of some sort to process them and compute forces (27, 29, 50). In most cases, the algorithm tracks the deflection of a structure of known stiffness, and thus Hooke's law is applied to compute the force. Using this method, sub-μN resolution is possible, while maintaining high flexibility of the sensor, which is able to be incorporated into a wide range of test beds due to its simplicity. Furthermore, the fact that it does not require any on-board electronics or a large footprint enables its use for wireless microrobots and other small scale systems. A few disadvantages of this sensor type include the trade-off between resolution and field-of-view (depending on camera's zoom level) and the fact that if an object blocks the view of the camera, force sensing is no longer possible. With the development of higher speed cameras and better discrete event cameras, this method is gaining traction and has a promising future in microforce sensing for microrobotics.

3. Robotics and control to measure and apply forces

Different solutions exist to create motions, deformations, or displacement. The main ones are tethered and untethered microrobotic systems (see section 6.1). All these technologies demonstrate high interest for the purpose of microforce sensing because they generate and control motions with enough Degrees-of-Freedom (DoF), resolutions and bandwidths to deal with the specificities of the small scales. They are also useful to set important parameters,

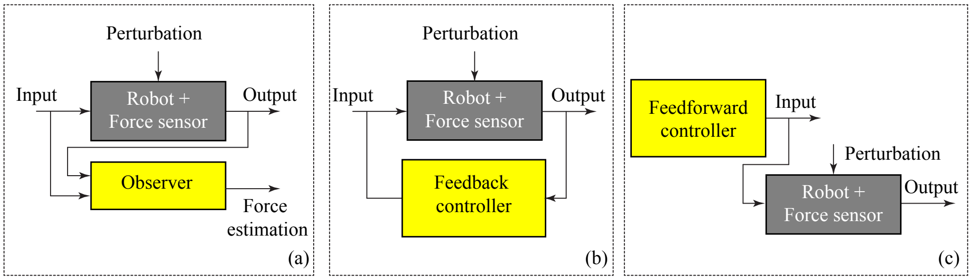

Figure 4

Schematic view of force estimation with (a) an observer, (b) force regulation with feedback and (c) feedforward controllers.

such as the speed or the acceleration of the motion which is important to consider during a force measurement.

Several control schemes have demonstrated their abilities to control position, deformation, or forces either in open or closed loop (51). Downscaling leads to a reduction in the mass of objects, and thus to an increase in their bandwidth. This raises a number of issues concerning the choice of hardware used for the control loop (real-time boards, FPGAs, etc.) and for acquisition (need for instruments with suitable bandwidth). The increase in bandwidth, coupled with the low orders of magnitude of the signals, implies a low signal-to-noise ratio. Manufacturing techniques lead to uncertainties in the dimensions of microrobotic systems, implying uncertainties in their models. Finally, the actuator non-linearities most commonly encountered at small scales are hysteresis and creep, consequences of the widespread use of piezoelectric materials for actuation and measurement. For this reason, a branch of automation is focusing on the control of small-scale systems through the design of control laws robust to uncertainties, non-linearities and noise (52). Particularly for force measurement, estimation and control, one can rely on techniques and methods for observation, regulation and disturbance rejection. Observation aims to estimate a force that cannot be measured directly. It often relies on the system model (e.g. robot, force sensor). The Luenberger state observer is one of the most widely used for linear time-invariant (LTI) systems. Its inputs are the system input and output, and its output is the signal to be estimated (Fig 4 (a)). When measurements are noisy in the bandwidth of interest, the Kalman filter is a well suited approach. This filter has been used in several microrobotics applications when a force has to be measured despite vibration and noises (53, 54). The disturbance observer is another structure that allows the estimation of a disturbance that affects the system (55). Thanks to this estimation, the perturbation can be rejected with an appropriate controller. Regulation is needed when the force has to be controlled. This is mainly the case for gripping force, contact force and breaking force. There are mainly two control strategies: feedback and feedforward (Fig 4 (b) (c)). The former is preferred because of its robustness but it is not always applicable especially when the force cannot be measured directly. In this case, the feedforward controller is useful but it requires a well-modeled system (56).

An explicit force control scheme is especially suited to dynamically control forces changing between the force sensing body and the sample, i.e. where there is always a contact between them (57). Nevertheless, for most applications, contact between the force sensing body and its environment are intermittent. In this case, free motion and constrained motions alternate, requiring a switch between position and force control (58). Control schemes enabling an efficient and smooth switch between them are available. During these alternating states, achieving force measurement at the microscale usually requires considering adhesion forces when contact occurs or when two surfaces come close together, i.e., typically a few hundreds of nanometers. These forces induce non-linear behaviors usually known as pull-in and pull-off effects, making control methods, such as impedance-based control that is able to dynamically control contacts, very important at the microscale (59, 60, 61). Robot control methods are also important to adapt to the changes in the environmental parameters, such as temperature or hygrometry, that are always influential at the microscale even in well controlled environments (62).

Robots also bring multi-DoF (Degrees-of-Freedom) capabilities that allow for several key advantages. First, they enable relative motion between a force sensing body and the sample to be characterized. This is useful to accurately select the point or area where the force has to be measured. This multi-DoF capability also enables the control of several important parameters, such as contact angles and relative orientation of motions or surfaces. Nevertheless, the number of DoF is always accompanied by an increase of the effects from imperfections of the robotic structure (63). It is possible for instance to measure and compensate for imperfections such as perpendicularity errors between axes by robot calibration (64). However, achieving force sensing by robots at the microscale requires to consider many more imperfections. Indeed, robots used for microforce sensing are very large compared to the volume of interest even if their motions have very high resolutions (typically nanometer level). Their imperfections can be high, inducing poor repeatability and accuracy (65). For instance, robotic stages used to achieve translation do not really succeed in moving along a straight line due to yaw, pitch, and roll parasitic motions, themselves induced by the mechanical guiding of the stages. Additional imperfections are also introduced by actuators whose physical principles generate vibrations. Also, even if most of the stages embed their own sensors enabling closed loop control at the joint level, this control has limited interest when the sensor provides indirect measurement of the motion (66). Many robots result from the concatenation of several elementary translation and/or rotation stages resulting in the stacking and increasing of these imperfections. Several studies have recently been done showing that robot calibration methods can significantly improve the positioning accuracy of such robots for micro (67, 68, 69, 70) and nanoscale purposes (65, 71). These methods consider both intrinsic (building and configuration of the robot) and extrinsic (relative position of robot, sensor, and environment frames) parameters that can be identified to compensate for the effects of these imperfections (72). The difficulty in achieving local and multi-axis measurement at the microscale makes this an active research topic despite the promising methods that have already been investigated.

4. Microforce sensor calibration

The calibration process is a crucial step in the development of every transducer, where the correspondence between the force $\overrightarrow{F_a}$ applied by a reference and the measured one $\overrightarrow{F_m}$ (Fig. 1 (b)) is identified and experimentally validated with a specific calibration setup and procedure. To obtain an accurate calibrated sensor, a key element is the definition of the reference used. Three principles are considered in the literature (73): (a) calibrated cantilevers, (b) other calibrated sensors, and (c) microbalances.

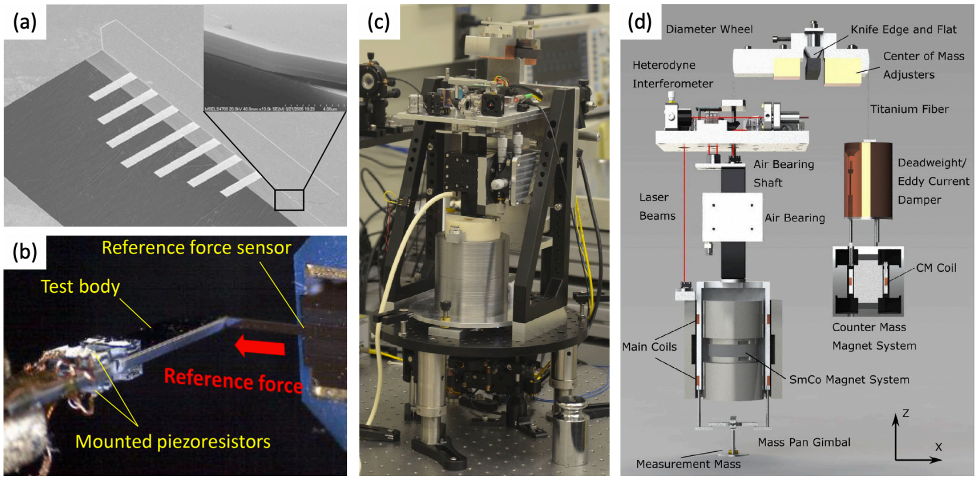

Figure 5

Calibration of microforce sensors using: (a) calibrated cantilevers (74)[1]; (b) a calibrated force sensor from (24) used as reference; and (c)(d) picture from and principle scheme of a compensated microbalance for traceable measurements from (75), respectively.

A calibrated cantilever can be used as force reference by measuring its bending and knowing its stiffness as exemplified in Fig. 5 (a). This technique is used when the deflection of the reference can be precisely determined during the force application. In (76), this technique is considered suitable for a force sensor with a precise external position measurement, as is the case for Scanning Probe Microscopy instruments like AFMs (77). If 1% of uncertainty can be reached, the trueness of the values will strongly depend on several parameters such as the position of the contact point and the Young modulus, leading in reality, to more than several percents of uncertainty (78).

The use of another microforce sensor such as (Fig. 5 (b)), considered as a reference, is quite widespread to calibrate a different microforce sensor (13, 79, 17, 80). In (81), a set of biocompatible sensitive SU-8 cantilevers with piezoresistive glass-like carbon gauges are calibrated using a commercially available and calibrated capacitive microforce sensor (FT-S1000). The variation of the output signal from the gauge is compared with the value of the reference from 150 μN to 8 mN with 20 μN static steps, actuated by a precise positioner. This way, bending can be approximated and then stiffnesses computed, from 6.3 to 72 N/m. The same calibrated sensor is used in (24) to characterise a microgripper with mounted piezoresistive silicon gauges. Tests are done from 0 to 9 mN, resulting in a 9 mN range and a calibrated stiffness of 5130 N/m.

These sensors have been calibrated using microbalances and measurement methods (Fig. 5 (c) and (d)) investigated by National Metrology Institutes (NMI) that especially investigates the notion of metrological traceability, which is defined as the *"property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty"* (82). Indeed, at the macro-scale, standard processes exists to ensure traceability of instruments

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such as ISO376-2011 for axial force transducers, but the microscale specific issues mentioned in Table 1, induce many technical and methodological challenges towards proposing a standard reference for forces below the Newton-level (83). In this scope, microbalances are seen as a solution to perform calibration in a more traceable way (16, 84, 85, 86). They generally have a plate on which the force is applied vertically at its center. In a compensated mode, the height of the plate is tightly controlled in closed loop, measured by a position sensor and actuated by an electromagnetic or electrostatic actuator. With that compensation, the contact point height remains precisely at a defined position, simplifying the calibration as only the force sensing body of the tested sensor is deformed during the process. This method is particularly widespread and has succeeded to obtain an extremely low overall uncertainty with a ratio of 2ppm for weight of 5g at NIST (87, 75) and allowed the redefinition of the kg with 0.01ppm (88). By taking into account practical issues as zero-point stability, angle deviation between the reference and measurement, and environmental changes, (89) was able to calibrate a capacitive force sensor of 200 μN, 2 mN and 20 mN ranges. A compensated balance was used at several NMI such as the German institute of metrology (PTB) and Swiss institute of metrology (METAS) that used the same measurement procedure with an external precise positioner used for the solicitation. Adding up all the influence factors, an uncertainty of 0.27% was obtained (90).

Calibration using another microforce sensor as reference are practical to set up and allow a versatile way to calibrate sensors, but, the uncertainty is at least several percents, because of the errors propagated from the transfer reference used. As it is described in (1), research on traceable calibration processes are being conducted in different places with NMI, most studies are based on microbalances and already obtained results demonstrate reduced uncertainties on results with comparative measurement (89).

5. Active microforce sensing

The most common force sensing technique is based on the measurement of the deformation δ of the force sensing body, whose stiffness k is known. Thus, the force measured in static mode is $k \times \delta$. Such sensors are called *passive sensors* (5, 4). The alternative *active sensors* working principle is based on force balancing between an unknown force and a known quantity (91). These sensors integrate an actuator controlled in closed loop to generate a force F_{act} that keeps the position of the sensing probe, and therefore the deformation of the sensing body, at a reference value δ_r when an external force F_{ext} is applied on it (Fig. 6 (a)). F_{ext} is the force to be measured. It is deduced from the control signal U_{act} to within a constant factor that is a function of the actuator's properties. The performance of passive sensors in terms of resolution, measuring range, and bandwidth depend on their mechanical properties. The stiffness is one of the most influential parameters. The lower the stiffness, the higher the resolution but at the cost of a lower measuring range and bandwidth. Typically, there is a trade-off between the resolution and measuring range on the one hand, and resolution and frequency bandwidth on the other. With active sensing, these trade-offs can be overcome (40).

The basic architecture of active sensors includes an actuator, a compliant mechanism, a position sensor, and a control algorithm for the probe's position regulation. When using MEMS technology, the electrostatic comb drive actuator is used most often (92, 40, 37, 38, 91). With a standard comb drive structure, the generated driving force is proportional to the square of the electric input voltage (92, 37, 38). To deal with this

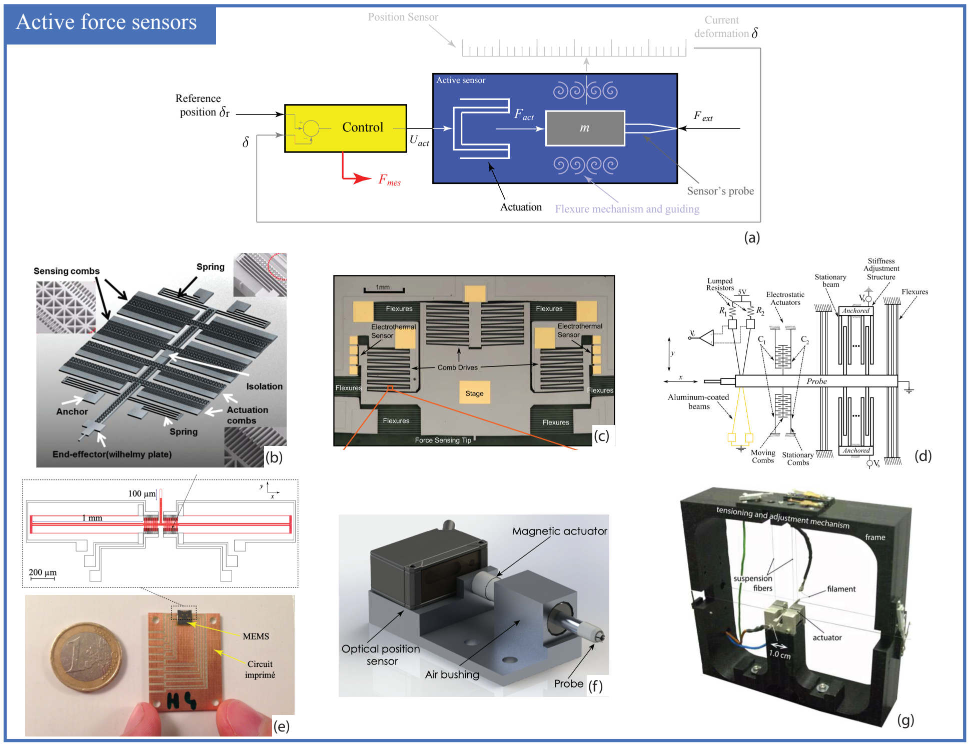

Figure 6

(a) Schematic view of an active force sensor working principle. (b) MEMS active force sensor with a comb drive actuator and folded flexures used for the measurement of the surface tension of various liquids (38)[2]. (c) Active sensor used for stiffness characterization of microcantilevers (92)[3]. (d) MEMS active force sensor with an adjustable stiffness mechanism (40)[2]. (e) MEMS active force sensor with a linear electro-mechanical characteristic (probe displacement/actuation voltage) (91)[3]. (f) Active force sensor based on a nil-stiffness guidance and an electromagnetic actuation (93)[3]. (g) Active force sensor used for haptics applications (39)[3].

non-linearity, several solutions have been reported by inverting the non-linear characteristic for linearization (94) or by instrumenting the actuator with a square root input voltage (92). This electrical nonlinearity can also be removed with a differential comb drive actuation (40, 91). For the compliant mechanism, the mechanical linearity (force/displacement relation) and the stiffness ratio (stiffness in the orthogonal direction of the measurement divided by the stiffness in the direction of the measurement) are the two main parameters that are considered for the selection of the appropriate architecture (95). For instance, with doubly clamped flexures, a mechanical non-linearity appears for large displacements leading to a so called *cubic stiffness*. This non-linearity can be handled with appropriate Linear Parameter Varying (LPV) controllers (96, 97). To measure the position of the probe in active sensors, several principles have been used such as capacitive (37, 38), electrothermal (92),

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piezoresistive (40), vision (91) and laser (39, 93) based. The control strategy used for the sensor's probe regulation is often designed as simple as possible. Reported techniques are based on integral control (92), IMC (Internal Model control) and resonant control (40), PID (Proportional Integral Derivative) control (38, 91) and state feedback control (93). Most of the time, the main issues in control are related to the precision in keeping the probe at a reference value, the damping of the oscillations, and the stability margin.

In (38), a MEMS force sensor is designed and fabricated based on a standard comb drive actuator with an integrated capacitive sensor (Fig. 6(b)). This sensor is able to measure forces up to 300 μN with a resolution of 25 nN. It has been used in closed loop for the measurement of the surface tension of various liquids. In (92), the sensor has been used for stiffness characterization of microcantilevers (Fig. 6(c)). In (40), a mechanism is incorporated to adjust the sensor's stiffness via an electrical voltage (Fig. 6(d)). The mechanism is based on an electrostatic actuator that generates a restoring force characterized by negative stiffness. This capability is useful when it comes to adapt the rigidity of the sensor to that of the object to be characterized. In (9), a dual-actuator assisted by a position feedback mechanism is integrated in a MEMS active force sensor. This original double actuator mechanism enables the sensor's sensitivity to be adjusted electrically, independently of the working position and the stiffness of the sensors' internal moving mechanical structure. In (91), the sensor incorporates a differential comb drive actuation and folded type flexure (Fig. 6(e)) making it an unique active MEMS sensor with a linear electro-mechanical characteristic (probe displacement/actuation voltage) reported in the literature.

In (93), an original active force sensor based on a nil-stiffness guidance and electromagnetic actuation is designed, fabricated, and experimentally tested for the measurement of a magnetic force (Fig. 6(f)). This sensor is suitable for the measurement of forces from the milli-Newton to the Newton range. Another original active force sensor based on a comb drive actuator is reported in (39). This sensor (Fig. 6(g)) integrates fibers as a compliant mechanism which allows the measurement of forces at very low frequencies (cut-off frequency around 10 Hz in open loop). The particularity of this sensor is that it has been coupled with a haptic interface which allowed numerous applications such as the feeling of capillary forces (39), the teleoperation with force feeling for injection in biological samples (98), and the feeling of what an insect feels like (99). Last but not least, an original passive nano-force sensor based on diamagnetic levitation has been reported in (53, 100). This sensor is particularly suitable for the measurement of nanoNewton forces at very low frequencies (few Hertz). The authors have presented a passive version of the sensor and are planning an active version in future works (100).

Active sensing is still an open research area. Research works have demonstrated several proofs of concept where actuation and control play a fundamental role in force sensing performance, e.g., resolution, sensitivity, measurement range and bandwidth. These performances can be tuned and modified on-line during a measurement process.

6. Microrobotic microforce sensing systems and applications

This section will focus on existing scientific instruments for microforce sensing using microrobotics. It will discuss the benefits and challenges of both tethered and untethered systems, providing examples of each and examine systems with embedded microforce sensing capabilities.

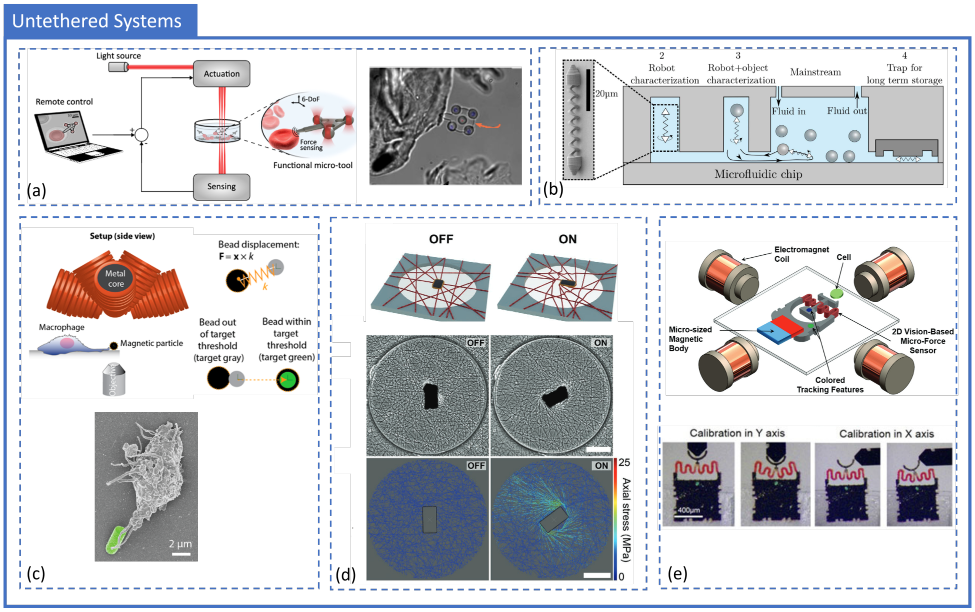

Figure 7

Untethered microrobotic systems with force sensing capabilities: (a) Force feedback is based on computer vision measurement of an optically driven microrobot for interactive biomanipulation (28)^2; (b) Helical microrobot used for force sensing inside a microfluidic chip (50)^2; (c) Force and torque sensing based on magnetic actuation and vision feedback for biological cell-robot interaction (27)^3; (d) Rotation of the μ-actuator resulting in spatially heterogeneous forces in the network, with tensile or compressive mechanical stresses dependent on the fiber orientation and local connectivity (101); (e) 2D vision-based microforce sensing with colored fiducials for biological or synthetic objects characterization (29)^3.

6.1. Untethered Systems

Untethered systems have the benefit of extra versatility and mobility in the workspace, since they are not bound to any larger subsystem (i.e.: power source, actuation module, etc.). Moreover, they are capable of reaching small areas and are even usable for *in-vivo* applications, where the size constraints are extremely tight and remote untethered operation is likely the only viable option. On the other hand, due to the fact that untethered systems have a limited footprint and need to have all its capabilities on-board (sensing, power, actuation, etc.), the types of force sensors that can be used in such systems are severely limited. For instance, force sensors that require some sort of circuitry for its measurements are most likely tethered, since there isn't enough on-board space for the electrical circuit and the measured forces need to be transmitted somehow to the operator. Therefore, most untethered microforce sensing systems usually rely on some type of optical or field-driven actuation and sensing.

For example, Gerena et al. (28) utilized optical traps to actuate microrobots and to also receive force feedback. In this work, the optical traps are able to move the beads shown in (Fig. 7(a)) and consequently the microrobot itself. As it pushes against a foreign object, a measurable change in displacement in the optical trap occurs, enabling the measurement of forces and torques applied to/by the microrobot. The use of optical traps (also called optical tweezers) is particularly significant when dealing with single molecule applications, as the maximum force and trap stiffness are directly proportional to the laser power of the system. Furthermore, there are other less complex force-sensing alternatives if pN resolution is not needed.

Recently, the use of vision-based force sensors, along with an untethered microrobotic platform, has gained some traction. This type of microforce sensor is extremely simple - it only requires a compliant structure of known stiffness and a method to track its deflection (usually via a camera feed). This way, a very small sensing footprint is attainable. Thus, the microrobot is able to provide the actuation and force application, while a vision-system tracks the deflections and computes the forces. Bardot et al. (50) (Fig. 7(b)), has used an untethered helical magnetic microrobot to measure pN-level forces inside a microfluidic chip using a vision-based sensing technique. The microrobot's actuation (input magnetic field strength and its resultant motion) were linked to the exerted force, obtained by a series of simulations and calibrations. By doing so, differences in the observed motion allowed the computation of the exerted forces inside the microfluidic chip.

Similarly, Schuerle et al. (27) (Fig. 7(c)) utilized magnetic particles to measure rotational or translational forces applied by a macrophage as it pulls a "prey" material. In this case, a vision-system tracks the position of the magnetic particle in real-time and, as the macrophage pulls it, a controller enables a magnetic actuation system to counteract the macrophage forces and keep the particle in place. By analyzing the needed input to the coil system, the force applied by the macrophage can be computed. Uslu et al. (101) (Fig. 7(d)) utilized untethered magnetic microactuators to deform fibrous extracellular matrices and apply desired forces. In this work, a digital twin experiment recreated using a computer vision algorithm, along with an accurate finite element model, are used to test virtual mechanical actuation schemes. This is of great benefit tissue engineering and mechanobiology fields, as studies of how applied forces to affect cells and tissues are crucial.

Guix et al. (29) (Fig. 7(e)) utilized a wireless magnetic microrobot with a vision-based force sensor to obtain real-time μN-level force sensing. This was done by utilizing a compliant spring-like structure, of pre-calibrated stiffness, and using a computer vision algorithm to measure its deflection, allowing for force computation via Hooke's law. A similar force sensing system has also been employed in tethered systems (102, 103) by utilizing a micropositioning stage instead of magnetic actuation, providing more spacial accuracy and enabling cooperative applications with force sensing, especially useful in fields of mechanical characterization of biological media and micromanipulation/microassembly. As previously mentioned, the use of vision-based force sensors provide a promising avenue for the next generation of force sensing microrobotic systems, especially untethered systems in which sensor footprint considerations are extremely important. With the development of higher speed cameras, vision-based force sensors become even more desirable, since higher resolutions at higher speeds are possible. Moreover, researchers are starting to investigate the use of discrete-time cameras as a possible solution to further improve sensing speed and resolution.

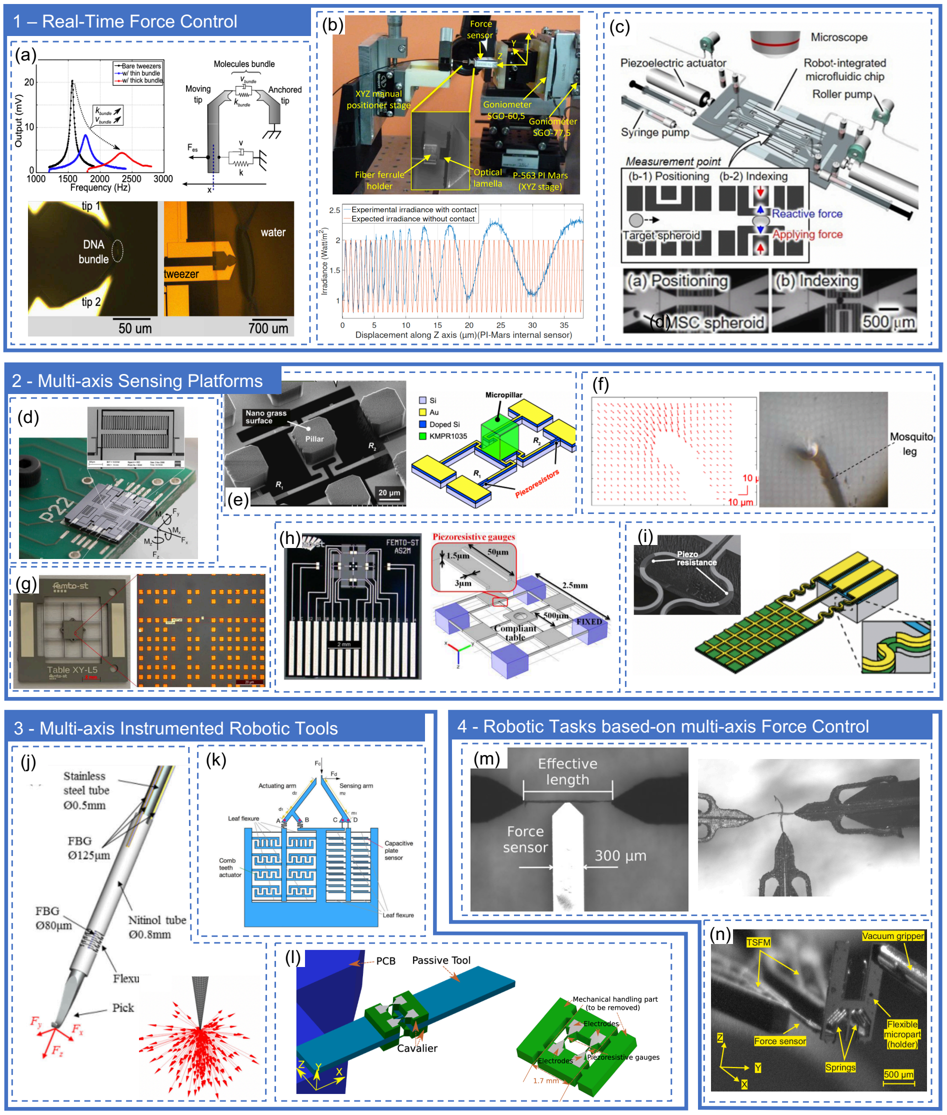

Figure 8

Tethered microrobotic systems with force sensing capabilities: -1- Real time force/position measurement: (a) Instrumented nanotweezers for mechanical characterization of DNA (104)[3](105) (b) Force-position sensing based-on photo-robotic approach (106) (c) Force-deformation compression inside of a Robot-Integrated Microfluidic Chip (107)[3]. -2- Multi-axis force and/or torque sensing Platforms (d) Six-Axis MEMS force–torque sensor (Capacitive) (7)[3] (e) Two-axis MEMS-based force sensor (Piezoresistive gauge) (108)[2] (f) Three-Axis force sensor (Vision) (15)[3] (g) Three-Axis microforce and torque sensing platform (Vision) (14)[3] (h) Multi-axis microforce and torque sensor (Piezoresistive gauges) (109)[4](i) MEMS two-axis force plate array (26)[1]. -3- Robotic tools integrating multi-axis force sensing capabilities: (j) Three axis force sensing instrument with integrated fiber Bragg (20)[3] (k) Dual-axis force sensing gripper for grasping a biocellulose (110)[5](l) Two-axis piezoresistive force sensing tool for microgripping (24) -4- Robotic tasks based on multi-axis force control: (m) Shear-mode bonding force and flexibility test of single pulp fibers (111) (112)[6](n) Hybrid force-position control for automated micro-assembly (113)[3](62, 114).

6.2. Tethered Systems

In tethered systems, the sensing instrument is usually attached to a micro/nanopositioning robotic system, allowing for several DoF and high motion resolution. Considering the generic configuration of Fig. 1, either the samples' substrate or the tip of the robot (robot's tool) can be instrumented. Several studies highlighted the importance to place the sensor body as close as possible to the contacts where the measurement takes place (115, 3). Fig. 8-1 introduces several examples: Lafitte et al. (Fig. 8-1a) shows that implementing the state feedback of an instrumented silicon nanotweezer enables the reduction of the resonant frequency of the system, improving the sensitivity of mechanical stiffness measurements and the bio-sensing of DNA molecules. Bettahar et al. (Fig. 8-1b) introduced a system combining a compliant structure with a laser so that optical Fabry-Perot interference's occur between them. High position measurement is achieved when a relative motion without contact happens based on sine optical measurements having a constant periodicity. Once a contact happens, the compliant structure deforms and the periodicity of the optical signal increases enabling to estimate the force applied resulting in a high resolution position-force measurement. Sakuma et al. (Fig. 8-1c) integrated a compliant structure inside of a microfluidic chip. Through the use of a piezoactuator and vision feedback, it induces a force-deformation compression of single-cell spheroids inside of a robot-integrated microfluidic chip. In addition, works related to the control with the view of mastering the grasping force for micromanipulation tasks have been addressed (116, 117, 118).

While the above mentioned works have dealt with the measurement of micro forces in one direction, several studies have naturally focused on the development of sensors capable of measuring in several directions, or force-torque sensing or force-position sensing together. In this scope, Fig. 8-2 highlights examples of multi-axis sensing platforms: the main works in the literature are based on a microfabricated compliant structures combined with: a six axis MEMS force torque sensor (using capacitive sensing) (7)(Fig. 8-2d); a two-axis MEMS-based force sensor (Piezoresistive gauge) to study capillary forces by measuring the interaction forces during the sliding of a droplet on a micropillar array (108)(Fig. 8-2e); a three-axis force sensor (vision) for detecting insect motion by evaluating deformation of a grid pattern inscribed in a flexible hydrogel sheet (15)(Fig. 8-2f); a three-axis microforce and torque sensing platform (vision) by tracking a periodic pattern inscribed on the platform enabling Fourier-based transform for accurate micro-assembly (14)(Fig. 8-2g); a multi-axis microforce and torque sensor (piezoresistive gauges) for measuring of friction forces where it is necessary to measure the pre-load as well as the lateral force (109)(Fig. 8-2h); and a MEMS two-axis force plate array to measure the ground reaction forces during the running motion of an ant (26)(Fig. 8-2i). Other works have also developed robotic tools integrating multi-axis force sensing capabilities. For them, the integrability of the sensing principle is a key challenge. Fig. 8-3 provides several complementary examples notably: a three axis force sensing instrument with integrated fiber Bragg grating for retinal microsurgery (20) whose principle can also be used for drug injection (119) or neurosurgery (120)(Fig. 8-3j); a dual-axis force sensing MEMS gripper for grasping a biocellulose (110)(Fig. 8-3k); and a

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two-axis piezoresistive force sensing tool for micrograsping micro-assembly (24) or control of gluing tasks (121)(Fig. 8-3l).

The majority of these instrumented platforms and instrumented robotic tools open the way to applications requiring simultaneous measurement in several directions, or to simultaneously measure force and position. Beyond the question of integrating all the devices together, the question of the dynamic response of the systems and the ability to control them together becomes a key challenge. Fig. 8-4 introduces several examples of such systems. In (111, 112) the authors develop a system to investigate the shear-mode bonding force measurement process and photocontrol of mechanical properties through flexibility test of single pulp fibers (Fig. 8-4m). The automated micro-assembly of compliant optical components using an instrumented microgripper and hybrid force/position control is demonstrated in (113, 114)(Fig. 8-4n). Accurate tasks are made possible by such multi-axis force sensing capabilities because they enable the implementation of robotic strategies that can be adapted to the presence of adhesion forces (62), to simultaneously controlling force and position (or force and vision) for tasks such as guiding, insertion or aligning of components (122, 123, 124, 125). Interests are also oriented to enable the robot to adapt to change in the stiffness of the working environment, such as for mini-invasive surgery tools. Li et al. (119) demonstrated that robot assisted ophtalmic surgery can be largely improved by 3D microforce perception that helps the surgeon to align and then guide the tool. There is also interest in applications such as elasticity sensing based on different tactile properties (126), to assist the micro-injection of both adherent and suspended cells by guiding the robot (2, 127, 128), and also for the purpose of mechanical characterization where multi-axis sensing and control enables the study of certain influential parameters. Govilas et al. (129) demonstrated that small angular errors during diametral compression tests of single plant fibers resulted in large errors in the estimate of their Young modulus (an angular error of 1°induces a 35% error) based on multi-axis force-position sensing (130). Associated with the accurate control of micropositioning robots, they proposed a robotic strategy to enable control of angles smaller than 0.1°.

All these works paved the way for the creation of tethered microrobotic systems for microforce sensing using different measurement principles, and have also enabled them to be used to achieve complex tasks by measuring local information such as contact forces. Ongoing progress in microfabrication techniques, notably 3D printing, and the improvement of interfaces enabling dynamic and synchronized control of several dynamic systems are key reasons to believe that these types of microrobotic systems for microforce sensing will develop strongly in the coming years.

7. Conclusions

The robotics and automation tools presented in this article are intended to help researchers to develop experimental devices capable of performing efficient microforce sensing, taking advantage of the intrinsic capabilities of microrobotic systems such as versatility, high dynamics, and multi-DoF motion capabilities. This paper aims to present for the first time an overview of force sensing systems by considering the robot, sensor, and control architecture as a whole.

A key perspective of microrobotic systems for microforce sensing is on the traceability where it is expected to provide, in the coming years, new standards and measurement protocols that could be applicable easily by researchers and industrials to guarantee the trueness of the measured force which is currently still an open question.

Most of microrobotic systems used for microforce sensing are commercially available today, but they still present several major limitations in terms of accessibility of sensor tips in hard-to-reach areas, and for the measurement of distributed forces. Many research teams are investigating new robotic principles that are expected to solve several of them, by increasing the miniaturization of robots end effectors and/or by designing soft robots or robots able to perform continuous deformations. These works will open avenues for different ways to control forces or to measure them. For instance, today most works are based on measuring a force at a contact point (or a small surface). Future perspectives might be oriented to the measurement of distributed forces to be made possible by smart materials and/or novel fabrication methods such as 3D/4D printing.

Last but not least, force based microrobotic systems under development enable to study different experimental protocols which currently provide a rich set of data, notably on force, position, deformation, temperature and so on. The sharing and analysis of these data should enable the exchange of best practices and the standardization of experimental devices and protocols. These data will also be important for the use of learning-based methods, useful for guiding people towards design, but also for the use of experimental systems in an optimal way to achieve efficient microforce sensing based on microrobotics.

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