International Journal of Advanced Robotic Systems

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ARTICLE

An Overview on Gripping Force Measurement at the Micro and Nano-scales Using Two-fingered Microrobotic Systems

Invited Feature Article

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Received 25 Oct 2013; Accepted 19 Dec 2013

DOI: 10.5772/57571

Abstract Two-fingered micromanipulation systems with an integrated force sensor are widely used in robotics to sense and control gripping forces at the micro and nano-scales. They became of primary importance for an efficient manipulation and characterization of highly deformable biomaterials and nanostructures. This paper presents a chronological overview of gripping force measurement using two-fingered micromanipulation systems. The work summarizes the major achievements in this field from the early 90s to the present, focusing in particular on the evolution of measurement technologies regarding the requirements of microrobotic applications. Measuring forces below the microNewton for the manipulation of highly deformable materials, embedding force sensors within microgrippers to increase their dexterity, and reducing the influence of noise to improve the measurement resolution are among the addressed challenges. The paper shows different examples of how these challenges have been addressed. Resolution, operating range and signal/noise ratio of gripping force sensors are reported and compared. A discussion about force measurement technologies and gripping force control is performed and future trends are highlighted.

Keywords Microrobotics, Microgrippers, Force Measurement, Control

1. Introduction

In microrobotics, the development of systems able to perform manipulation tasks at the micro and nano scales has been a dominant research topic for many years [1][2][3][4][5]. Achieving efficient and safe grasping tasks at such scales is one of the main challenges. This requires the use of a micromanipulation system (Figure 1) that includes both actuation and force sensing in dimensions adapted to micro-scale objects.

Usually, a micromanipulation task can be done with or without a direct mechanical contact between the object and the micromanipulation system [6]. Contactless manipulation techniques have the advantage of not generating adhesion forces between the object and the system. But the blocking forces applied to the object are weak and the gripping forces cannot be controlled. Moreover, such techniques are often dedicated to the manipulation of objects with specific physical properties.

Optical tweezers [8][9][10], dielectrophoretic systems [11], magnetic manipulators [12][13], ultrasonic and levitation manipulators [14][15] are amongst contactless micromanipulation systems. A mechanical contact between the object and the system allows a controllable gripping force. Typically, capillarity-based systems [16], adhesion effectors [17] [18], vacuum microgrippers [19][20][21] and two-fingered micromanipulation systems[1] [22] are based on such a manipulation strategy. Vacuum microgrippers are nowadays the most widely used micromanipulation systems. They have many advantages for pick and place operations and especially for releasing problems due to adhesive issues. Vacuum microgrippers are nevertheless ill-adapted for the assembly of objects whose size is lower than 100 μm and they do not provide degrees of freedom (DOF) for an orientation of the object. Two-fingered micromanipulation systems are in this case more efficient. Hybrid-type microgrippers (i.e., a two-fingered micromanipulation system with an integrated vacuum tool) [23] take advantage of the two technologies.

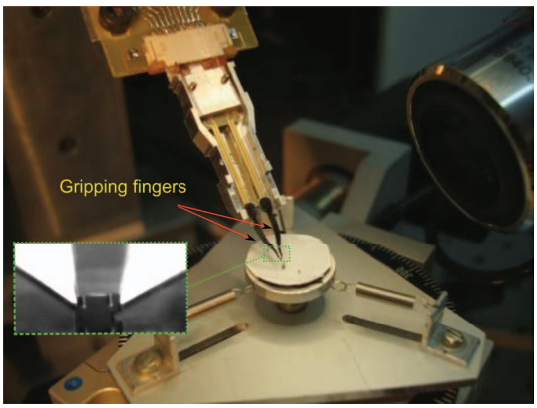

Figure 1. MMOC (Microprehensile Microrobot On Chip) [24]

This paper focuses on two-fingered microrobotic systems and especially with those able to sense and control gripping forces. A common architecture of such systems is built with two distinct mechanisms (Figure 2):

- An actuation mechanism: allowing the grasping of the object. This mechanism has an actuated finger. The free end of this finger is in contact with an object during a grasping task. The actuated finger can be made of an active or passive material (respectively: [25], [2]). An actuator is attached to the finger to perform the motion in the latter case. Actuated fingers predominantly exist in the cantilever configuration. Their lengths range from a few hundred micrometers to several dozen millimeters.
- A measuring mechanism: allowing the position and/or force measurement. This mechanism has a measuring finger which performs position and/or gripping force measurements. Active or passive materials are also used here (respectively: [26], [2]). A sensor is attached to the measuring finger when its material is passive. The length of this finger is usually the same as the actuated finger.

Some micromanipulation systems do both things (actuation and measurement) with a single finger [27]. In addition, the ability to measure gripping forces is not part of every two-fingered micromanipulation systems [28].

Mastering a micromanipulation task through the measurement and the control of the gripping force shows itself to be a critical issue in the field. This problem is extremely complex due to the non-linear dynamic of actuation mechanisms at the micro-scale, and the very low ratio between data signals and the noise. Adhesion and attraction phenomena at the micro/nano-scale, such as van der Waals molecular interaction, electrostatic forces and capillarity, add to the encountered difficulties.

Noise is the main disturbance during grasping tasks. This pseudo-random and poorly known phenomenon defines the resolution of the gripping forces that can be applied to an object. The required force resolution for a given micromanipulation task is related to the object elasticity. For instance, during an object grasping, the displacement of an actuated finger[2] of 1 N/m stiffness with a 380 nm amplitude causes a 10% deformation of a hydrogel microcapsule [29]. If the amplitude of the noise (which can be due to vibrations of the fingers) is of the order of hundreds of nanometers only, the manipulated hydrogel microcapsule can be damaged. Moreover, if the measurement noise of the gripping force sensor it is too high, the microgripper is not able to detect the object [30] (i.e., the amplitude of the signal provided by the force sensor does not change before and after the grasping).

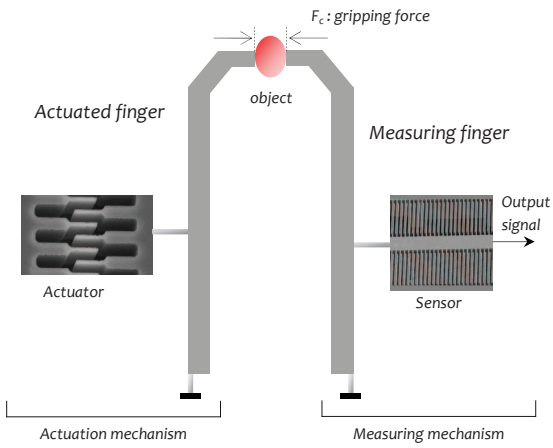

Figure 2. Simplified scheme of a micromanipulation system composed of anactuation mechanism and a measuring mechanism

Both force and position resolutions are decisive factors in the feasibility of a micromanipulation task, thus, specific care has been given to the design of new actuation and measurement devices for microrobotics over the past 20 years. The aim is to obtain systems with an increasingly better resolution to be compatible with dimensional and dynamic characteristics of the objects to be manipulated. Thanks to these technological breakthroughs, it is theoretically possible to obtain a force

[1] These systems are also called two-fingered microrobotic systems, microgrippers or microtweezers.

[2] This displacement allows compressing the object.

resolution down to the nano-Newton using capacitive force sensors [3], or even down to the pico-Newton with optical measurement techniques. However, it is barely possible to reach such resolutions in actual systems because of the noise and vibration disturbances strongly occurring at small scales. In gripping force sensors, noise amplitude can vary from hundreds of nano-Newtons to few micro-Newtons. They can be inherent to the micromanipulation system, but also originated by the working conditions. This high diversity of possible reasons for their existence makes it hard to identify where they come from and how they influence the resolution [31].

This paper deals with an overview of gripping force measurement using two-fingered micromanipulation systems. The paper focuses on measurement technologies, resolution, operating range and signal/noise ratio of gripping force sensors and their use in microrobotic applications. The main challenges to increasing the efficiency of micromanipulation tasks are highlighted using different examples. The work provides a general view on issues of gripping force measurement and control at the micro-scale, the main achievements and the future trends.

2. Force measurement

At the micro-scale, the range of gripping forces that must be applied on manipulated objects depends on the application. It can vary from few nano-Newtons to several tens of milli-Newtons. It is possible to define three types of application requiring the measurement and the control of gripping forces [32]:

- Applications requiring a sufficient gripping force to overcome the adhesion force or to break two homogeneous solids. For example, a gripping force of 114 μN is required to overcome the adhesion forces for the manipulation of a Silicon cube with an edge length of 1 mm and a striction coefficient of 0.1. Moreover, to separate (break) a Carbone Nano Tube (CNT) from its substrate, the minimal required gripping force is 60 μN [33].
- Applications dealing with the manipulation of fragile materials. For instance, the manipulation of a lipid bilayer requires gripping forces ranging from 0.215 μN to 11 μN in order to obtain a deformation of about 5 μm [34].
- Applications requiring the characterization of the mechanical properties of highly deformable soft materials such as biological cells. Here, gripping forces of the order of the nano-Newton are needed [29].

The resolution and the operating range are therefore the two main characteristics of a gripping force sensor. A trade-off between such characteristics is often made taking into account the application for which the microgripper is meant. The force measurement is generally deduced from the deformation of a flexible device whose stiffness is known. The deformation can be measured either from the modification of some properties of the force sensor, such as the resistance or the capacitance, or from a direct measurement performed optically. Measurement methods using capacitive, piezoelectric and piezoresistive effects are the most prevalent in robotic micromanipulation.

2.1. Piezoresistive force sensors

This measurement principle is based on the use of piezoresistive strain gauges. The variation of the resistance of a piezoresistive material is proportional to its deformation. One of the fundamental parameters of a strain gauge is the sensitivity to strain. Quantitatively, it is expressed as the strain factor G_f:

$$\frac{\Delta R_s}{R_s} = G_f \frac{\Delta L}{L} \tag{1}$$

where:

$$R_s = \frac{\rho L}{A} \tag{2}$$

R_s and L are respectively the nominal (before deformation) resistance and length of the strain gauge. ΔR_s and ΔL are respectively the resistance variation and the length variation of the strain gauge due to its deformation.

Generally, the variation of the resistance is translated into an analogue voltage V_{out} using a Wheatstone bridge. For the configuration of Figure 3:

$$V_{out} = \left(\frac{R_4}{R_4 + R_3} - \frac{R_2}{R_2 + R_s} \right) V_{in} \tag{3}$$

R_2, R_3 and R_4 are fixed resistances. They are chosen such as $R_s = \frac{R_3 R_2}{R_4}$ (the bridge is said to be balanced and $V_{out} = 0$).

In micromanipulation systems, strain gauges are glued on the sensing finger where the deformation is the most important. Therefore, when an external force (i.e., gripping force) is applied on the tip of the sensing finger, a deformation is produced. The resistance variation of the strain gauge is measured. Taking into account the strain gauge deformation and the stiffness of the sensing finger, the gripping force is deduced [26]. The main advantage of strain gauges is that they allow the measurement of high amplitude (in the order of milli-Newtons) forces, but it has a limit in terms of miniaturization [3]. Moreover, the accuracy of the measurement depends on how the strain gauge has been glued.

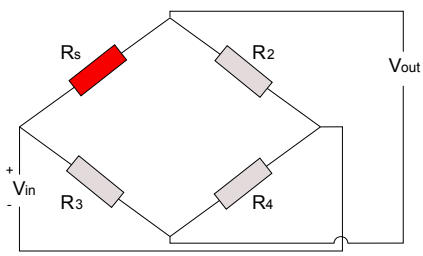

Figure 3. A strain gauge sensor within a Wheatstone bridge

2.2. Piezoelectric force sensors

The measurement principle is based on the direct piezoelectric effect. When a piezoelectric material is mechanically stressed, it generates an electrical signal. A piezoelectric force sensor can be fixed on a sensing finger

[3] One of the smallest strain gauges used in microrobotics has a lateral length equal to 1 mm [32]

[35] to account for the mechanical stresses applied on it. The sensing finger can also be made entirely of a piezoelectric material [22]. Poly Vinylidene Di Fluoride (PVDF) polymers are among the most commonly used piezoelectric materials for force sensing at the micro-scale. Such a sensor is for example used in [35] to measure forces down to 100 μN. Piezoelectric force sensors have good performances in dynamic mode but are limited when measuring static forces [36].

2.3. Capacitive force sensors

The main drawbacks of the above-mentioned force sensors are the hysteresis non-linearity, the high sensitivity to temperature variation and the incompatibility of the fabrication processes with CMOS[4] technologies. Capacitive force sensors are a solution to such limitations. They consist of a set of flat capacitors which include a fixed electrode and a movable electrode. The set of movable electrodes is attached to the sensing finger on one side and is connected to a fixed structure through a compliant mechanism (i.e., suspension) [2] on the other. Capacitive sensors allow measuring small displacements deduced from the variation of their capacity. The latter being the result of the displacement of mobile electrodes, it is conditioned into an analogue voltage. The mechanical stress applied to the sensing finger can be deduced from the displacement measurement and the stiffness of the suspensions. Generally, capacitive sensors consist of several layers of capacitors in the form of interdigitated combs. With this architecture, the variation in capacitance resulting from the displacement of the movable electrodes is greater and the measurement range is more important.

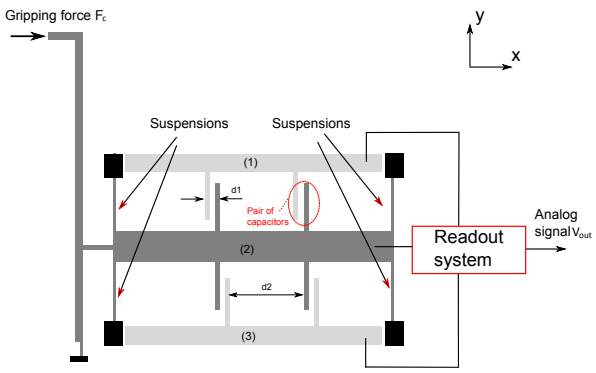

Figure 4. Simplified scheme of a capacitive force sensor connected to a measuring finger. Fixed electrodes are (1) and (3). The moveable electrode is (2).

Figure 4 shows a simplified scheme of a capacitive force sensor connected to a measuring finger. Electrode (1) and (3) are the fixed ones and the electrode (2) is the movable one. When a gripping force F_c is applied to the system, the electrode (2) moves in the direction of the x axis. Electrodes (1,2) and (2,3) are two capacitors of capacities C_1 and C_2 respectively. The readout system allows translating $\Delta C = C_1 - C_2$ into an analogue voltage V_{out} (i.e., $V_{out} \propto \Delta C$). For example, in [2], the readout chip MS3110 by MicroSensors [37] is used for gripping force measurements through relation (4).

$$F_C = S_v \times (V_{out} - V_1) \tag{4}$$

$$S_v = \left[\frac{Gain \times V_{ref} \times 1.14 \times (N_b \varepsilon A)}{2C_F} \frac{\left(\frac{1}{d_1^2} - \frac{1}{d_2^2}\right)}{K_{sb} D_b} \right]^{-1} \tag{5}$$

where: $Gain$, V_{ref}, C_F and V_1 are programable parameters of the MS3110 readout chip. K_{sb} is the stiffness of the suspensions and D_b is an amplification parameter. N_b is the number of pair of capacitors, A is the area of the capacitors and ε is the permitivity of air.

Capacitive sensors can be embedded monolithically into the so-called MEMS-based microgrippers [29] [38].

2.4. Optical force sensors

In seminal works, Atomic Force Microscopy (AFM) has been a reliable tool for the measurement of forces at the nano-Newton scale. The bending of a silicon cantilever in contact with a surface[5] is measured using an optical sensor which can be a 4 quadrants photodiode or a laser interferometer (Figure 5). If the stiffness k of the cantilever is known, the measured bending y_c is translated into a quantitative force information F_c through relation (6).

$$F_C = k \times y_c \tag{6}$$

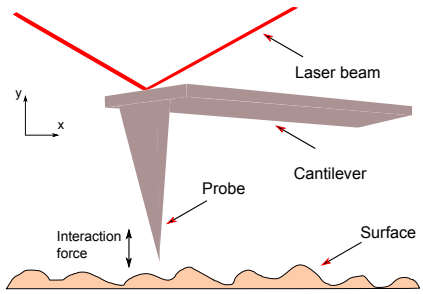

Figure 5. Force measurement using an AFM cantilever

Due to their high resolution, AFM cantilevers are often used as gripping fingers for micromanipulation tasks requiring very small gripping forces [39][40]. This principle is used in [41] for the manipulation of microspheres (diameter ranging from 3 μm to 4 μm). The fingers of the microgripper are two AFM cantilevers (Figure 6.a). The micromanipulation task is performed with the measurement of the normal force (normal to the substrate). The measurement of the normal force at different steps of the manipulation tasks is shown in Figure 6.b. It is possible to observe the range of forces that the microgripper must be able to measure for such tasks.

One of the major drawbacks of this measurement principle lies in the uncertainty of the cantilever stiffness. This uncertainty is mainly due to the fabrication process and

[4] CMOS: Complementary Metal Oxide Semiconductor.

[5] An interaction force is exerted between a surface and the cantilever tip which causes the bending of the cantilever.

Measurement principle	Advantages	Drawbacks	Resolution
Piezoresistive	ease of use, measurement of high amplitude forces (order of the mN)	low resolution, limited in terms of miniaturization	0.5 mN [49]; 0.3 mN [50]; 0.5 mN [51].
PVDF	suitable for the measurement of dynamic forces	not suitable for the measurement of static forces.	few μN [52]; < 100 μN [35].
Capacitive	high resolution, can be embedded monolithically	low measurement range	0.01 μN [53]; 50 nN [2].
optical	very high resolution for both static and dynamic measurements	low measurement range, the accuracy of quantitative measurements depends on the accuracy of the stiffness calibration, bulky	few nN [54]; < 1nN [55].
Vision	very high resolution for static measurements, measurement of forces along several axes, high measurement range	not suitable for the measurement of dynamic forces, bulky	3 nN [46].

Table 1. Summary of the main characteristics of some measurement principle used for gripping force measurement at the micro-scale

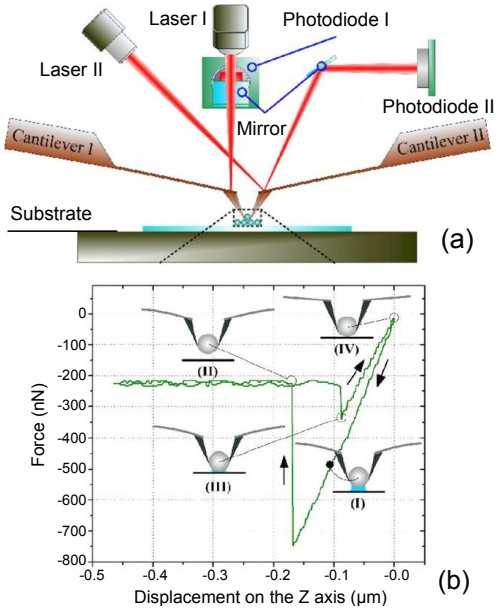

Figure 6. Manipulation of microspheres with force measurement using two AFM cantilevers (a). Measurements of the normal force at different steps of the micromanipulation task [41].

leads to uncertain quantitative force measurements. As such, the stiffness calibration of AFM cantilevers has for many years been an open research field [42][43][44][45]. One of the widely used calibration methods is the so-called *thermal calibration*. It consists of the calculation of the stiffness k taking into account the temperature T expressed in Kelvin, the Boltzmann constant K_b and the root mean square (r.m.s) of the thermal noise y_{rms} around a bending mode (equation (7)[6]). The accuracy of this method is in the range $5-20\%$ [45].

$$k = \frac{K_b T}{y_{rms}^2} \tag{7}$$

[6] In (7), k is the *effective* stiffness of the cantilever corresponding to the bending mode used for the measurement of y_{rms}.

The measurement system is not embedded within the microgripper which greatly reduces the degrees of freedom of the robotic micromanipulation system.

2.5. Force measurement by vision

The detection and the measurement of the deformation of a structure by vision allows the measurement of a force. Such a method is used in several studies dealing with micromanipulation [46][47]. This measurement technique does not require any instrumentation within the microgripper, it allows the measurement of static forces with a very high resolution (nano-Newton resolution) and gives a view of the scene where the micromanipulation tasks are performed. It is of particular interest when performing manipulation tasks in a Scanning Electron Microscope (SEM). Nevertheless, vision is often a bulky solution and is not suitable for the measurement of high frequency dynamic forces due to the demanding data processing. The acquisition speed of cameras is of primary importance for dynamic force measurement.

2.6. Discussion about force sensor resolution

Table 1 summarizes some of the characteristics of the main measurement principles used for gripping force measurement at the micro-scale. It is shown that the resolution of a force sensor is related to the physical principle used to sense gripping forces. A strain gauge allows obtaining a milli-Newton force resolution when it is glued to a millimetre-sized measuring finger and a micro-Newton force resolution with a micrometer-sized measuring finger. PVDF sensors allow force measurements below 0.1 μN and MEMS capacitive force sensors are able to perform force measurement at the nano-Newton scale. Force measurement at the pico-Newton scale requires, however, optical measurement techniques. Related resolutions are nevertheless only evaluated theoretically. This can be found in already published reviews on force measurement at the micro-scale [48] [26]. From an experimental point of view, theoretical force resolution has little practical

significance because of the influence of the environment on micrometer-sized systems (vibrations, etc.), the very weak signal to noise ratio of measurements and the high dynamic of some forces at the micro-scale.

In what follows, the overview focuses on the use of force sensors with two-fingered micromanipulation systems. The paper emphasizes the performance of measurement systems in *experimental conditions* and shows the advancement of measurement technologies (to be compatible with the specifications of the micro-objects) in chronological order. This is the main contribution of the paper.

3. Two-fingered micromanipulation systems and force measurement at the micro-scale

Most micromanipulation systems with an embedded force sensor are dedicated to the manipulation and the characterization of soft and highly deformable biomaterials. In this section, a chronological overview of gripping force measurement using two-fingered micromanipulation systems is presented. The focus centres on the evolution of measurement technologies regarding the requirements of microrobotic applications. Several examples are given but the list of reported prototypes is not exhaustive.

3.1. From 1992: the extensive use of strain gauges

Summary: micromanipulation tasks were mainly performed on rigid objects. Resolutions below the micro-Newton scale were not required and objects were generally manipulated with gripping forces of several milli-Newtons except for a few cases. The first microgripper with an integrated force sensor was proposed and the first experimental gripping force control (with feedback) at the micro-scale was demonstrated.

The use of strain gauges for force measurement at the micro-scale has been very common in microrobotics [1, 56–58]. The first prototype of a micromanipulation system with an embedded force sensor was developed in Japan in the early 90s [1]. The microgripper was made of a piezoelectric bimorph actuator and four strain gauges. The strain gauges allowed the measurement of the bimorph position and the gripping force. The maximum force amplitude that could be measured was 15 mN. In 1998, the IBM Almaden Research Center designed a piezoresistive strain gauge with a theoretical resolution of 2 nN. This technology was transferred as part of a microgripper design (Figure 7) which included a piezoelectric actuator [59]. The effectiveness of the microgripper has been proven experimentally for the manipulation of a 5 μm diameter glass ball. A 350 nN gripping force has been applied without feedback control. According to the literature, this microgripper was unique in being able to measure gripping forces at the nano-Newton scale with the use of strain gauges.

One of the first experimental micromanipulations involving the measurement and the feedback control of gripping force was demonstrated in [58, 60]. The designed

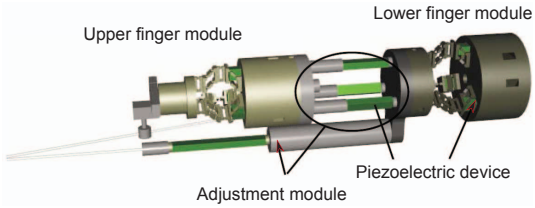

Figure 7. Micromanipulation system with embedded piezoresistive strain gauges for the measurement of the gripping force [59]

microgripper consisted of a piezoelectric actuator and a strain gauge glued on one finger. A Proportional Integral (PI) controller was used to control the position of the actuated finger to come in contact with the object to be manipulated and also to control the gripping force. Gripping force control was achieved for the manipulation of an optical fibre. The latter was handled with 1.2 mN gripping force amplitude and the measurement noise was $\approx$ 122 μN. Due to this noise, the microgripper was not able to apply controlled gripping forces below the micro-Newton scale. Such force amplitudes are required for a safe manipulation of highly deformable materials (see Section. 3.4).

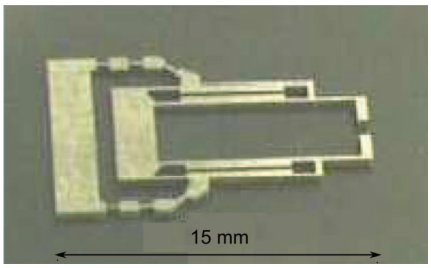

Figure 8. Prototype of the microgripper used in the biomedical field [61]

An improved version of the microgripper (Figure 8) was reported in [61]. According to the authors, the signal to noise ratio of the measurement force was improved thanks to the use of four strain gauges. This microgripper was used to characterize the stiffness of skin cells by measuring the shift of the resonance frequency of the system when grasping.

3.2. From 2000: Toward the measurement of forces at the nano-Newton scale by the use of external measurement systems

Summary: studies have been done aiming at sensing and controlling forces at the nano-Newton scale. The first works dealing with this issue were performed using external force measurement systems. Interesting solutions have been proposed but the methods required bulky equipment and did not allow the micromanipulation systems to perform high speed pick and place operations.

Zhou and Nelson [55] proposed a microgripper including two AFM cantilevers as fingers (Figure 9). The first cantilever could be moved thanks to a piezoelectric actuator and the second cantilever was used as a force sensor. The deflection of the second cantilever was measured using a Photodiode. A proportional controller

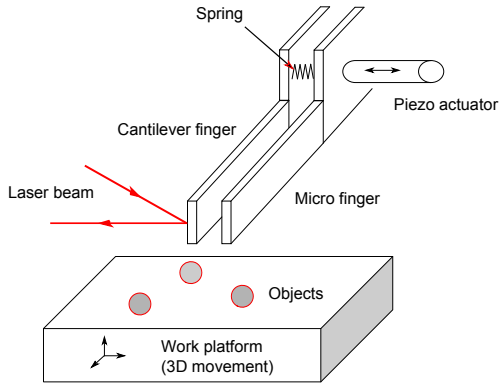

Figure 9. Microgripper consisting of two AFM cantilevers (fingers): the measurement of the gripping force is performed with a photodiode (optical principle) [55]

was designed to control the gripping force applied by the microgripper on objects whose size was less than 100 μm. The micro-objects were handled with 100 nN and 200 nN gripping forces. The smallest force that could be measured with this system was equal to 2 nN. The use of the optical principle for force measurement is of great interest when dealing with the manipulation of highly deformable materials requiring gripping forces of the order of the nano-Newton. However, as mentioned in Section. 2.4 one of the main drawbacks of this solution is that the measurement system is not embedded within the microgripper. Therefore, the micromanipulation system is not able to perform automated pick and place operations easily.

The use of vision allows increasing the dexterity of robotic micromanipulation systems and it offers the possibility of measuring forces along several axes. Wang et al. [62] used a finite element model and a vision algorithm for the measurement of the gripped object deformation and therefore to deduce the gripping force. Greminger and Nelson [46] developed a method that visually measures the force distribution applied to a linearly elastic object using the contour data in an image. This method was applied when the microgripper consisted of an AFM cantilever. The force resolution was equal to 3 nN. It has been proven that vision is a powerful tool to measure forces with very high resolution (nano-Newton scale) in static mode. Nevertheless, external measurement systems are mostly bulky solutions. The challenge at this time was to design new sensor technologies which could be embedded within microgrippers with resolutions close to those obtained by optical or vision measurement principles.

3.3. From 2003: Toward embedded and high resolution force sensors

Summary: studies have been conducted aiming at sensing and controlling forces below the milli-Newton scale with embedded force sensors. In most applications, measurement resolutions were not yet sufficient for a safe manipulation of highly deformable objects. The first prototypes of multiple degrees of freedom micromanipulation systems have been proposed.

Embedding high resolution force sensors within microgrippers has been an important issue in microrobotics. In this period, several physical measurement principles were studied with the aim of designing embedded force sensors with a nano-Newton resolution. Agnus et al. [22] proposed in 2003 the MMOC[7]. The fingers of the microgripper allowed a planar motion to grip an object and an out of plane motion for the alignment. The microgripper was actuated by two piezoelectric cantilevers with silicon finger tips as end effectors. The force measurement could be performed using the self-sensing technique [63]. This technique theoretically allowed obtaining a force resolution of a few micro-Newtons.

The MMOC was used in several applications including the manipulation of silicate micro-sized particles [64] for biological applications. In [35], a PVDF force sensor was embedded within a microgripper. This micromanipulation system was used for the assembly of optical micro-components. The smallest gripping force that could be measured was equal to 3.2 mN with a noise measurement equal to 300 μN. This microgripper allowed the sensing of gripping forces below the milli-Newton scale. The measurement principle used in this microgripper was modified in [66, 67]. The first strain gauge was attached to the actuated finger for position measurement and the second strain gauge was fixed on the sensing finger for the measurement of the gripping force. The gripping force was controlled for the manipulation of an optical fibre of 230 μm diameter. The smallest gripping force that was applied in this application was 3 mN. The use of PVDF did not allow the measurement and control of a few micro-Newton forces at that time.

Manipulating objects with gripping forces at the milli-Newton scale has been found to be limited in the biological field. Kemper [30] demonstrated experimentally that with a force resolution of 2 mN, the object that could be detected by the microgripper through the force sensor needed to have a Young's modulus greater than 1.8 MPa. For this purpose, a microgripper embedding a strain gauge force sensor (2 mN resolution) was designed (Figure 11). The gripping force was deduced thanks to the method proposed in [58]. As illustrated in Figure 12, the microgripper was able to detect a human hair gripped with a force of 64 mN. However, the microgripper failed to detect an Expancel microsphere[8] due to its insufficient force resolution. The Young's modulus of some materials and biological cells are presented in Figure 10 as comparative values. This study demonstrates the urgent need for high resolution force sensors in biological applications.

A multiple degrees of freedom (DOF) microgripper was also reported in [65]. The system has more DOF than the MMOC, it is mainly composed of four stack actuators: two piezoelectric bender actuators and two piezoelectric stack

[7] MMOC: Microprehensile Microrobot On Chip

[8] Expancel microspheres are thermoplastic particles provided by AkzoNobel (http://www.akzonobel.com). They are composed of a polymer shell encapsulating a gas. They are deformable, soft and resilient.

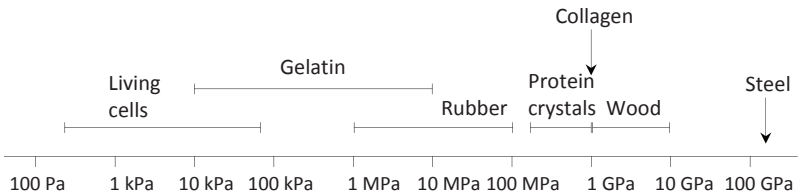

Figure 10. Young's modulus of different materials [30]

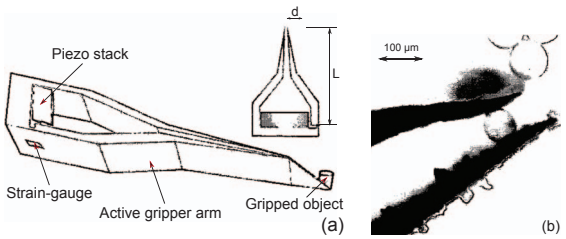

Figure 11. Microgripper actuated with a piezoelectric stack actuator and an embedded strain gauge force sensor: (a) simplified scheme of the microgripper, (b) fingers gripping an expancel microsphere [30]

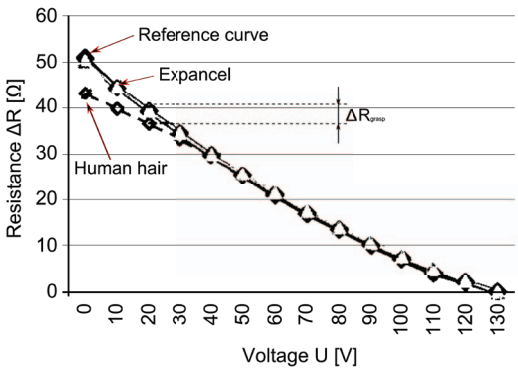

Figure 12. Deduction of the gripping force from the strain gauge resistance change ΔR. The force sensor was able to detect a human hair while an Expencel microsphere could not be detected [30]

actuators (Figure 13). Each tip of the gripper has three DOF. Ten strain gauges were embedded within the system (one for each stack actuator and four for each piezoelectric bender). The strain gauges were used for position measurement but could also be used as gripping force sensors. This microgripper was one of the few systems that achieved automatic dexterous micromanipulation with two fingers.

3.4. From 2006: The use of MEMS-based microgrippers with embedded capacitive force sensors

Summary: significant advances were made in the field with the development of MEMS-based microgrippers and capacitive force sensors. The first prototype of such a system was proposed. The first gripping force control at the nano-Newton scale with an embedded force sensor was demonstrated. The efficiency of MEMS-based microgrippers and embedded capacitive force sensors for the manipulation and the mechanical characterization

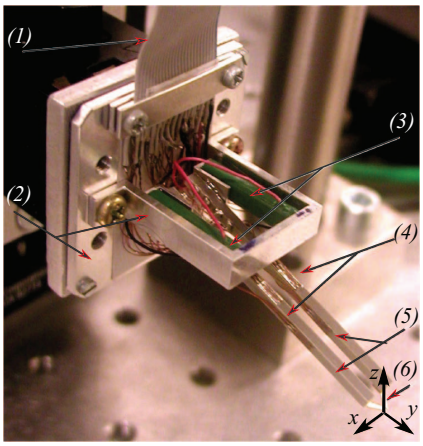

Figure 13. 6-DOF microgripper and its main components: 1. electronic connection, 2. frame, 3. piezoelectric stacks, 4. strain gauges, 5. 2D piezoelectric benders, 6. detachable tips. [65].

of biological cells was demonstrated. Most of the manipulated objects in this period (highly deformable) could not be gripped with safety using microgrippers of the first and the third period. Compared to the solutions of the second period, the microgrippers of this period could easily perform pick and place operations with the ability to sense forces at the nano-Newton scale.

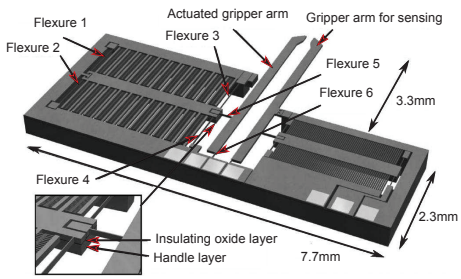

Figure 14. Monolithic microgripper with an embedded capacitive force sensor [68]

In 2006, Beyeler et al. [68] developed the first prototype of a monolithic MEMS-based microgripper with an embedded capacitive force sensor. The microgripper included in the same substrate a comb drive actuator which allowed the motion of an actuated finger and a capacitive force sensor attached to a sensing finger (Figure 14). The theoretical resolution of the force sensor was equal to 50 nN. Obtaining such a resolution with an embedded force sensor was a significant result compared to microrobotics state of the art. Nevertheless, this

resolution could not be obtained experimentally due to measurement noise (see Table 2). Several applications involving the use of this microgripper have been made [2] including the manipulation of micrometer-sized glass balls and the manipulation of biological cells. The glass ball was gripped with a 380 μN force amplitude. The smallest gripping force that could be efficiently measured by this system was equal to 8 μN. The manipulation of the biological cell was performed without force measurement. The authors do not specify if the cell was detected by the force sensor.

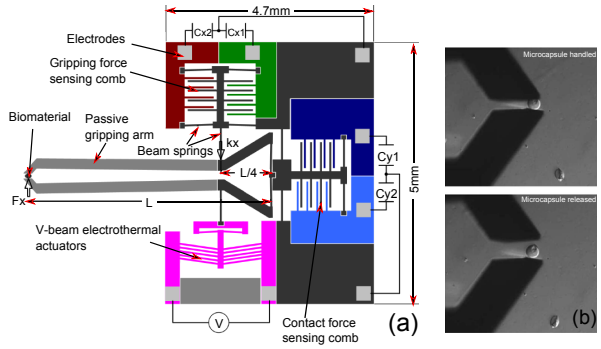

Figure 15. (a) Monolithic microgripper with embedded capacitive force sensors along two axes [3, 29]. (b) Micromanipulation of a hydrogel microcapsule with controlled gripping force [3]. 374.65 nN gripping force leads to 10 % deformation of the microcapsule [29].

Capacitive force sensors allowed an easy measurement of gripping forces in the order of a few tens of micro-Newtons when handling micrometer-sized objects. Kim et al. [3] embedded two capacitive force sensors within a monolithic MEMS-based microgripper (Figure 15). The first sensor allowed contact detection (theoretical force resolution: 38.5 nN) while the other was used for gripping force measurement (theoretical force resolution: 19.9 nN). This microgripper demonstrated a gripping force control at the micro-Newton force level [3]. Biomaterials ($\sim$ 20 μm diameter) have been manipulated with controlled gripping force using a PID output feedback controller. The smallest gripping force applied to the biomaterials was equal to 2 μN [3]. In this study, the authors showed that even if the resolution of the gripping force sensor was 19.9 nN, it was not possible to apply controlled gripping forces below the micro-Newton scale due to noise. The experimental measurement resolution was found to be equal to 500 nN [3].

In [70], the authors improved the signal to noise ratio of measurement and demonstrated (using the same microgripper) the first experimental gripping force control at the nano-Newton scale. To this end, the microgripper was used for the manipulation of interstitial cells (10-20 μm diameter). The smallest controlled gripping force was equal to 60 nN. Nevertheless, the authors do not explain how the signal to noise ratio of the force sensor was improved.

The same microgripper was used in [71] for the mechanical characterization of highly deformable hydrogel microcapsules (15-25 μm diameter). In this application, the microcapsules were coated with chitosan. The variation of the percentage of chitosan coating changed the mechanical properties of the microcapsules.

The characterization results presented in Figure 16 can be compared with the theoretical values of the Young's modulus of some biological cells (see Figure 10). For example, the Young's modulus of a human red blood cell (erythrocyte) is equal to 26 $\pm$ 7 KPa. For the elastic characterization of the microcapsules, a deformation model of a sphere was used in [71]. Such a model allows for an explanation as to why in [30], the microsphere Expancel could not be detected by the microgripper due to its poorer force measurement resolution. Indeed, in [30] it is shown that the Young's modulus of the Expancel sphere is lower than 1.8 MPa. Assuming that the Young's modulus of the sphere was equal to 1.5 MPa and that the gripping force was equal to 2 mN (resolution of the force sensor in [30]), the deformation model shows that for a 2 mN gripping force, a 100 % deformation of the sphere is obtained. In other words, the sphere is destroyed and can not be detected by the microgripper. The need for nano-Newton sensing resolution for the efficient manipulation of soft and highly deformable biomaterials is then demonstrated.

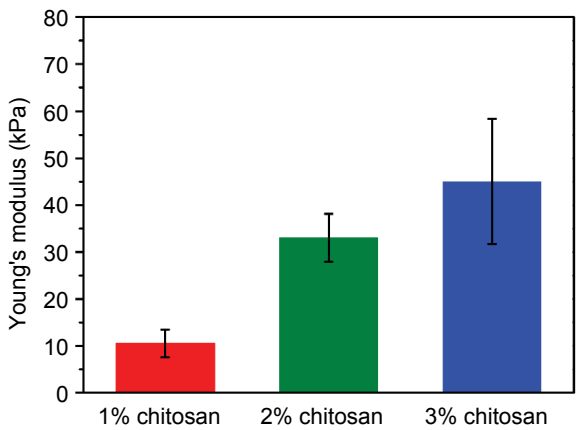

Figure 16. Young's modulus values for a microcapsule with 1%, 2%, and 3% chitosan coating [71]

In [72], a microgripper with an embedded piezoresistive force sensor allowed obtaining a theoretical resolution of 770 nN. The smallest force measured experimentally was equal to 30 mN. The authors did not demonstrate a gripping force measurement below the micro-Newton scale, probably due to noise.

In addition to integrate force sensors, innovative solutions have been proposed to increase the dexterity of microgrippers. For example, in [73], a microgripper with four fingers has been designed to allow the grasping of three objects at the same time. Piezoresistive force sensors are attached to two fixed fingers and a piezoelectric actuator moves the two other fingers. The first resonance frequency of the fingers was defined so that the effect of the environmental noise (mechanical vibrations and acoustic noises) on the vibration of the fingers is reduced and therefore the resolution of the force measurement is increased. The resolution of the force sensor was 3 μN and

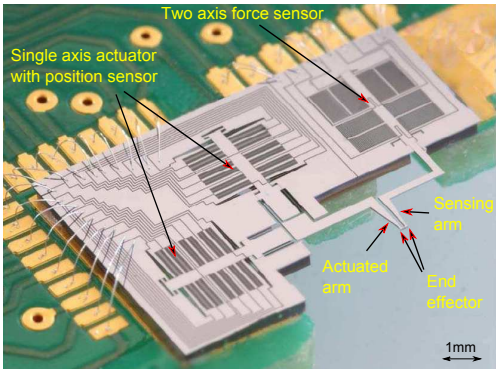

Figure 17. Microgripper with both an embedded single axis capacitive position sensor and a two axes capacitive force sensor [75]

the noise amplitude was equal to 20 μN. This microgripper is then not suited for the efficient manipulation of highly deformable objects such as the hydrogel microcapsules of [71] but could be a very interesting tool to increase the speed of a microassembly process due to its ability to manipulate several objects at the same time.

In 2010, Muntwyler et al. [75] proposed a prototype of a microgripper with both an embedded single axis capacitive position sensor and a two axes capacitive force sensor (Figure 17). The position sensor was used for the measurement of the displacement of the actuated finger and the force sensor was capable of measuring forces up to $\pm$ 60 μN with a resolution down to 60 nN. For this microgripper, the force resolution of the sensor was demonstrated experimentally and was not affected by an additional noise in the measurement [75]. This microgripper is therefore very attractive for biological applications.

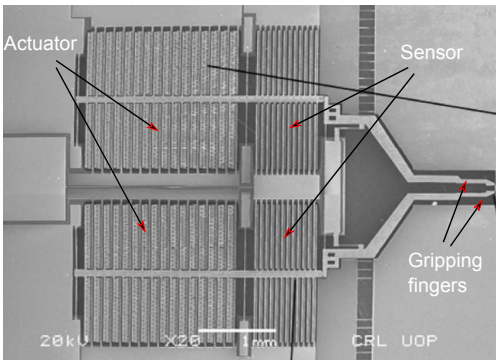

Figure 18. Microgripper with embedded two electrostatic comb drive actuators and two capacitive force sensors [74]

Capacitive sensors can also be used for both the measurement of the fingers' positions and the gripping force. Bazaz et al. [74] proposed a prototype of microgripper consisting of two comb drive actuators and two capacitive sensors that has these two properties (Figure 18). Each finger was connected to a comb drive actuator and a capacitive sensor. As such, each finger could be moved toward the object to be manipulated and the fingers' positions could be measured. To increase the measurement resolution, the fingers were designed so that their first resonance frequency was equal to 4.5 kHz. The microgripper has been used for the manipulation of an optical fibre (55 μm diameter) with 200 μN gripping force.

4. Discussion

In Table 2, the main characteristics of the sensors for gripping force measurement are summarized. The range of forces that could be measured experimentally are given in Figure 19. The amplitude of the measurement noise is most of the time much higher than the theoretical resolution. The noise amplitude can be different between two force sensors even if they are working with the same physical principle. It is possible to compare for instance the force sensors used in [2], [3] and [75]. The noise amplitude does not solely depend on the working principle of the force sensor. Although the electronic measurement chain has a significant effect on the noise amplitude and therefore on the resolution, vibrations of the fingers also have an important effect on the measurement resolution. To address this issue, in some works [73][74] the fingers are designed so that their resonance frequency is located outside the bandwidth of the environmental noise. Environmental noise influence can explain why in [3] the measurement of the gripping force could not be performed below the micro-Newton, while in [70] the same force sensor has been used for a nano-Newton force control at the micro-scale. Nevertheless, in most publications, the origins of the noise are supposed but not clearly defined. This issue remains an open research direction in microrobotics [31] and especially for applications requiring nano-Newton force resolutions (e.g., biological applications).

Using a nanometre resolution gripping force sensor is not sufficient to manipulate a material with a nano-Newton gripping force. It is also necessary that the actuated finger is able to perform nanometre displacements when gripping an object. As an example, in [55] the sensing finger has a stiffness equal to $0.3N/m$, the 2 nN gripping force amplitude is obtained thanks to the displacement of the actuated finger with a 6.66 nm amplitude. Controlling the gripping force at the nano-Newton requires in fact, first and foremost, to achieve a controlled positioning of the actuated finger with nanometre displacements. If the amplitude of the uncontrollable vibrations of the actuated finger exceeds a few tens of nanometres, then they would directly disturb the measurements via the force sensor, making it difficult or impossible to apply a gripping force of a few nano-Newtons in amplitude. Performing an accurate nano-positioning of the gripping fingers for the manipulation of highly deformable materials such as those used in [30] [29] is of primary importance.

Figure 19 shows that very few studies dealt with gripping force control. At the micro-scale, soft materials have mechanical properties (stiffness and damping) close to that of the actuation and sensing mechanisms of microgrippers. Therefore, during a gripping tasks, a classical set of soft materials (e.g., cell samples) have enough variation to induce instabilities in gripping which can cause damage to the gripper or the sample. In

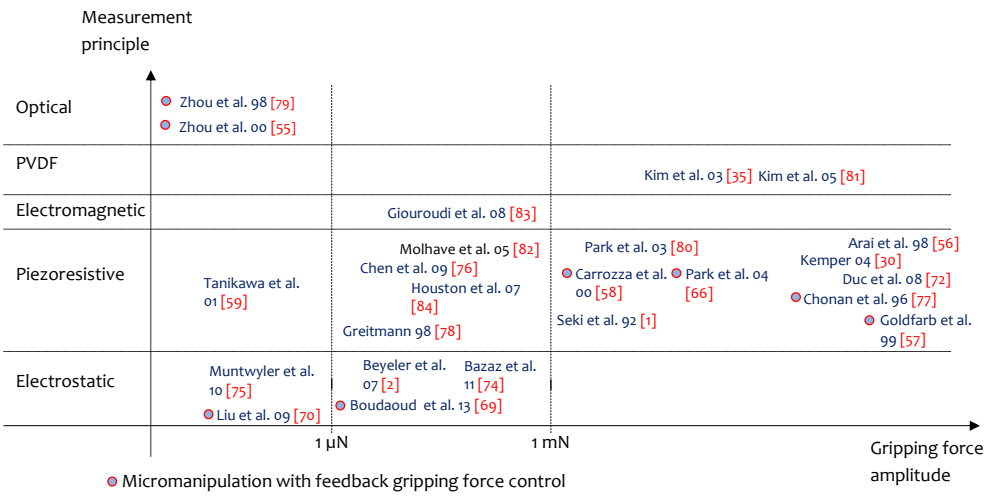

Figure 19. Range of forces measured experimentally by microgrippers

the literature, micro-scale force feedback control designs are mostly based on PI, PID or LQG (Linear Quadratic Gaussian) schemes [70][58][67][69]. Controller synthesis is often achieved considering the mechanical properties of a single sample and closed loop performances are validated experimentally when gripping the sample used for the synthesis [69][70]. It is nevertheless hazardous to grasp an object with different properties to the one used for the synthesis. Especially in the case of biology applications, similar samples have consequent variations in size and stiffness.

Another important point is that the required finger stroke to grip an object can vary from a few tens of nanometres to several hundreds of micrometers, depending on the application. The stroke of an actuated finger depends on the size of the object to be manipulated. Nevertheless, a trade-off between positioning resolution and displacement range is most of the time performed. It is in fact rare that the fingers of a microgripper can do both nanometre displacements and displacements of several tens of micrometers.

5. Conclusion and future trends

5.1. Conclusion

The development of micromanipulation systems that include both actuation and gripping force sensing in dimensions adapted to micrometer-sized objects opens the way to novel and cost-effective applications from microassembly to cell mechanical characterization. In the early 90s, researchers focused on the development of microgrippers for the manipulation and the assembly of rigid materials for which milli-Newton gripping forces were adapted to most of applications. Biological applications opened up a new direction for the development of gripping force sensors. The biological samples are highly deformable soft materials. They are very sensitive to applied force and how they are handled. The use of two-fingered micromanipulation systems for their manipulation calls for precise force measurement and control at the nano-Newton scale. This particular issue is evidently not limited to biological samples and is a general concern nowadays for micro and nano-scale manipulation (e.g., manipulation of CNTs, manipulation of thin blades in TEM[9], etc.). This paper has given an overview of major works performed in gripping force measurement using two-fingered micromanipulation systems. The focus centred on the evolution of measurement technologies regarding the specifications of microrobotic applications and especially on the development of force sensors with resolutions adapted to the mechanical properties of manipulated objects. In conclusion, this paper summarizes major examples of gripping force sensors and their key performance measures, namely the resolution, the signal to noise ratio and the amplitudes of the gripping forces applied in the experiments.

5.2. Future trends

Even though significant achievements have been reached in force measurement and control at the micro-scale, several issues have not as yet been addressed. Some studies have demonstrated the interest and the effectiveness of force control at the nano-Newton scale. The control of forces along two orthogonal axes at the same force scale has not been demonstrated. This can be very efficient when the orientation of the manipulated object is required [65]. The overview presented in this paper shows that optical [55][79] and capacitive [3] force measurements are the main techniques that allow experimentally sensing and controlling forces at such scale. But MEMS-based microgrippers (using capacitive sensors) and AFM cantilevers (using optical measurement) are ill-adapted to orientation tasks. In this case, the prototypes reported in [64] and [65] are more appropriate, but they use piezoelectric and strain gauge measurement systems for which no demonstration of force sensing below 100 nN has been demonstrated. Appropriate control strategies can be used for this purpose. First, as the fingers of the prototypes [64] and [65] are millimetre-sized, their first resonance frequency is relatively low making the

[9] TEM: Transmission Electron Microscopy.

Force sensor type	Measurement performance/noise	Gripping force max/min	Year	Reference
Strain gauge	*	15 mN/*	1992	[1]
Strain gauge	*	several tens of mN/*	1996	[77]
Strain gauge	0.1 μN (accuracy)/*	2 mN/*	1998	[56]
Piezoresistive	0.2 μN (resolution)/*	500 μN /*	1998	[78]
Photodiode	< 1 nN (resolution)/0.03 nN	140 nN/ 2 nN	1998	[79]
Strain gauge	*/≈122 μN[60]	22 mN /1.2 mN[60]	2000	[58]
Photodiode	< 1 nN (resolution)/0.03 nN	200 nN /2nN	2000	[55]
Strain gauge	2 nN (resolution)/<100 nN	600 μN /350 nN	2001	[59]
Strain gauge	667 μN/V (sensitivity) /*	1.3 mN /*	2003	[80]
PVDF	39.5 mN/V (resolution)/≈150 μN	60 mN /3 mN	2003	[35]
Strain gauge	2 mN (resolution)/*	380 mN /64 mN	2004	[30]
Strain gauge	12.82 mN/V (sensitivity)/*	23 mN /3 mN	2005	[67]
PVDF	39.5 mN/V (resolution)/*	18 mN /5 mN	2005	[81]
Piezoresistive	*	15 μN /*	2005	[82]
Electrostatic	50 nN (resolution)/2.35 μN[69]	380 μN / 8 μN	2007	[2]
Electromagnetic	*	130 μN / 18 μN	2008	[83]
Electrostatic	19.9 nN (resolution)/500 nN [3]	50 μN/ 60 nN [70]	2008	[3]
Piezoresistive	770nN (resolution)/*	*/ 135 mN	2008	[72]
Piezoresistive	3 μN (resolution)/≈20 μN	1.2 mN/ 100 μN	2009	[73]
Piezoresistive	5 μN (resolution)/*	500 μN/ *	2009	[76]
Electrostatic	60 nN (resolution) /60 nN	60 μN/60 nN	2010	[75]

Table 2. Summary of the main characteristics of gripping force sensors in two-fingered microrobotic systems. The notation "*" indicates that the characteristic is not given in the reference. Gripping force max/min and noise are experimental measurements.

fingers sensitive to the environmental noise [31] and therefore the measurement resolution can be lower than the theoretical one. A proper characterization of such noises (accurate noise models are needed) and appropriate control strategies for noise rejection are essential to reach nano-Newton force resolutions. The coupling between the degrees of freedom of the fingers is also an important issue from the control point of view. The influence of the uncertainties of the mechanical properties of manipulated objects on the stability of the micromanipulation system requires the use of robust controllers. Another important point is that most gripping force measurement and control techniques do not tackle the issue of the *impact force*[10]. This issue is rarely discussed in the literature. Zho et al. [79] demonstrate the need for hybrid force/position controllers in micromanipulation to reduce the effect of the impact force which can cause damage to the object. It is shown in [79] that for a force reference of 2 nN, the hybrid controller can reduce the impact force from 140 nN[11] to 9 nN. Performing hybrid force/position control for the manipulation of biological cells is an interesting research direction. This overview has summarized the range and the experimental measurement resolutions of force sensors in two-fingered micromanipulation systems operating in air. Since more and more applications require performing manipulation and characterization tasks in Scanning Electron Microscopes, it would be very interesting to evaluate the influence of the vacuum on measurement resolution. To the best of the author's knowledge, gripping force control in a vacuum has not been demonstrated in the literature. More generally, force measurement and control along one or multiple axes is a great challenge in microrobotics. Indeed, it is fundamental to achieving fully automated assembly and characterization tasks at the micro-scale with efficiency and a high repeatability.

[10] The impact force appears at the moment when both actuated and measuring fingers come into contact with an object (the reader can refer to [79] for more details)

[11] The impact force of 140 nN is obtained when only a force controller is used (no hybrid controller).

6. References

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