Title: Micro-Nano-manipulation

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Definition: technology enabling to grasp, move, characterize and/or position an object whose characteristic size is lower than one millimeter.

Overview:

The characteristics of the Micro-Nano-manipulation are linked with the specificities of the behavior of the objects whose characteristic size is lower than one millimeter. These objects are usually defined by the terms micro-object, nano-object or micro-nano-objects considering objects respectively with a characteristic size between 1 millimeter and 1 micrometer, lower than 1 micrometer or both previous cases. The terms microworld, nanoworld or micro-nano-world are also used to define respectively the collection of micro-objects, nano-objects, or micro-nano-objects (see fig. 1).

The definition of the characteristic size varies depending on the object's shape. For spheres, cubes or cuboids, all the dimensions have the same order of magnitude, the characteristic size can be defined respectively as the diameter, the square dimension or the average of the dimensions. For membranes in which the thickness is one or several order of magnitude below the other dimensions, two characteristic dimensions can be considered, the thickness and the average of the two other dimensions. Currently, the most used terminology is the term "nanomembranes" when the thickness size is below 1 micrometer. For wires, two characteristic sizes can also be considered, the wire length and its diameter. The most used characteristic size is the diameter. Indeed, a "nanowire" means a wire with a diameter lower than 1 micrometer.

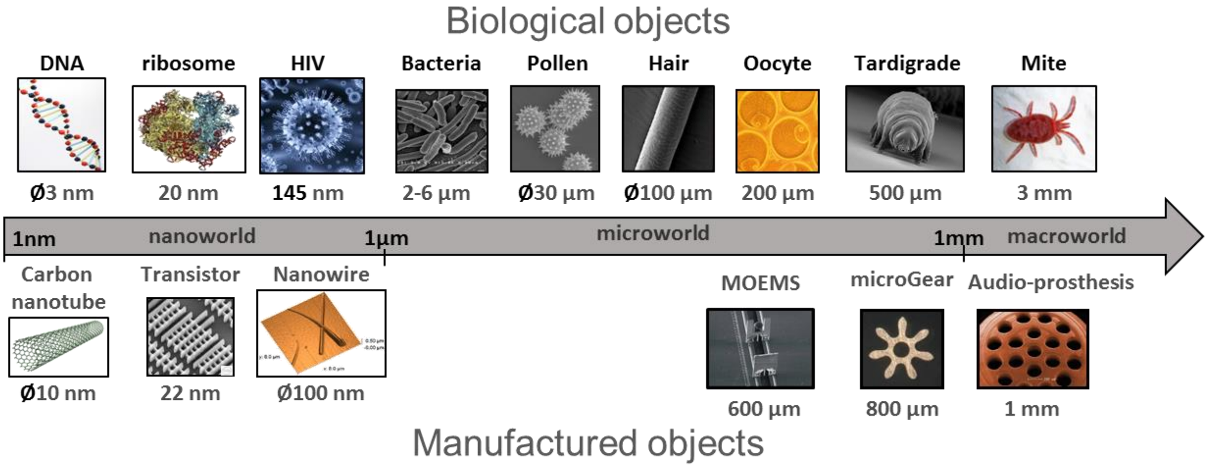

Fig 1. Example of biological objects and manufactured objects in micro-nano-worlds.

The behavior of objects in micro-nano-world is directly linked to the impact of the miniaturization on physical effects (Lambert, 2013; Chaillet and Régnier, 2013). Every physical effect (e.g. forces) applied to an object or physical properties of an object (e.g. mass) is a function of the size of the object. The volume effects (e.g. inertia, weight), usually predominant in human scale, depend on the volume. The surface (e.g. adhesion) and linear effects (e.g. surface tension), usually predominant in micro-nano-world, depend respectively on the surface and the size of the object. Indeed, the comparison of a large object and a small object having respectively a size L and L/10, shows that the volume effects on the smaller object is 1,000 times smaller than on the larger one, when the linear effects are only 10 times smaller. The fact that the miniaturization has a different impact on every physical effect or properties is called "scale effect".

In everyday life, the scale effect explains the fact that insects can stay on the water surface or on a vertical wall. Indeed their weight (volume effect) becomes negligible compared to surface tension on the water surface (linear effect) or surface adhesion on the wall (surface effect). In micro-nanomanipulation, objects weight and inertia become negligible compared to other physical effects such as adhesion or viscous effects in liquids. This scale effect on physical properties requires to completely re-invent actuation technologies (e.g. piezomotor) and grasping technologies (e.g. non contact manipulation) to manipulate objects in micro-nano-world (Sun and Liu 2015; Zhang et al. 2018).

The scale reduction also affects the fabrication technologies. Indeed the technologies used to build macroscale objects (machining, cutting, etc.) cannot be used in micro-nano-world. Micro-nano-objects are usually built using microfabrication methodologies which are inspired by microelectronics and MEMS technology based on chemical etching, chemical deposition using photoresist resins. These technologies enable to build $2D^{1/2}$ objects. These technological limitations induce constraints on the microrobotic tools design such as the force sensors (Komati et al. 2016). Indeed both the compliant structure and the deformation or displacement sensing principle have to be compatible with microfabrication technologies. Recently, 3D micro-objects have been built using (i) two-photon 3D microprinters (Gerena et al. 2019), (ii) using origami enabling to go from 2D structures to 3D components or (iii) using robotic micro-nano-assembly.

The third large impact of the scale reduction concerns the position measurement and object localization. During micro-nanomanipulation the localization of the object is mostly based on vision. Optical microscopes are able to provide picture of micro-objects whose size is larger than 1 micrometer. Indeed the usual resolution in optical microscopes using visible light is related to the wavelength of the light (380-780 nm). For objects, whose size is lower than 10 micrometers, the electronic microscope, having a better resolution, is preferred (electron has a significantly smaller wavelength than photons). In the case of nano-objects, the Atomic Force Microscope - AFM - is also usually used and can be used both as an imager and a manipulator. The principle of the AFM is completely different from electronic and optical microscopes, a microscale cantilever measuring atomic forces is scanning the sample enabling to define its nanoscale topology. Recently, impedancemetry has also been used to measure the position of micro-objects in a fluidic channel (Brazey et al. 2018).

The scale reduction on physical effects, fabrication technologies and measurement technologies create an original scientific paradigm for robotic micro-nanomanipulation in which all the robotic functions have to be redesigned. The actuators and tools have to compatible with dominant physical effects and fabrication technologies. The choice of the robotic components is significantly driven by the technologies constraints. The controller has to be robust (i) to the non-linearity of the new actuation principles, (ii) to the disturbance coming from the environment, (iii) to the parametric uncertainties and (iv) to the low level of signal/noise ratio of the sensors. Moreover as the natural frequency is increasing when the size of an object is reduced, the bandwidth of the micro-nano-manipulation devices is usually high (more than 100Hz). Dynamic control is thus particularly challenging in micro-nano-world requiring high speed position acquisition (e.g. event based camera (Gerena et al. 2019-2) or high speed camera (Dkhil et al. 2017)) and a high sampling frequency of the control card (Zemanek el al. 2018).

Key research findings:

Two different approaches are proposed in the literature to perform controlled micro-nanomanipulations. The first approach named “contact manipulation” consists in placing an end-effectorin contact with the manipulated objects. It enables to reach high handling and blocking force but the adhesion forces between the gripper and the object disturbs the release of the object. The second approach consists in using a remote force field (e.g. electrostatic, magnetic, etc.) to move the object without direct contact. It avoids gripper/object adhesion disturbances but the blocking force are very low and could be not sufficient for real case assembly (e.g insertion).

Contact micromanipulation

Vacuum grippers: the most used gripping method in the industry to perform micromanipulation is the vacuum gripper. The object is suck on a surface using depression. The major advantage is the simplicity of the gripper that has no degree of freedom. However, the method is highly disturbed by adhesion force and object release cannot be obtained in a precise way for objects whose size is below 50 micrometers. Moreover, fragile objects or objects without a planar surface cannot be grasped with vacuum grippers. One of the first robotic system using this principle has been proposed by Zesch et al. (Zesch et al. 1997) to grasp tiny diamonds whose characteristic size is close to 100 micrometers. Nowadays, it is widely used for electronic die bonding machine (e.g. surface mounted device –SMD- components) (Ha et al. 2017, Yang et al. 2019).

Micro-tweezers: The second popular way to manipulate micro-nano-objects is to use micro-tweezers (see fig. 2). A large majority of micro-tweezers consists in uses two-fingers to grasp a large variety of micro-nano-object shapes (Xie, 2020). From the industrial point of view, micro-tweezers are more and more used in robotic micro-assembly machines enabling to grasp a large variety of objects contrary to vacuum grippers. Because of the adhesion, the object can also be grasped with only one finger in the micro-nano-world. In nanoscale, lot of scientific works have been done using Atomic Force Microscope (AFM) tips as a robotic end-effector able to measure forces (Fukuda et al. 2003; Xie et al. 2009).

Moreover, *dexterous* micro-tweezers have been developed in order to provide (in micro-nano-world) a dexterity approaching that of the human hand, (Zhou et al. 2006). They are based on three to four fingers in order to perform in-hand manipulation including rotation capability (Cappelleri et al. 2011; Seon et al. 2018). All these approaches propose a large versatility but the release is still highly disturbed by adhesion forces between the end-effector and the manipulated object.

Other contact grippers: Some other approaches have been proposed in the literature to grasp micro-nano-object. As capillarity is one of the predominant force in microscale (Lambert, 2013), some grippers pick up micro-objects with a water or oil droplet. It enables to grasp objects with various shapes and induces natural compliance which is interesting in micro-assembly tasks (Lambert et al. 2003; Sariola et al. 2011). The release of the object has been a technological problem during years and recent works propose an original gripper geometry enabling to provide efficient release (see fig. 3) (Dehaeck et al. 2019).

In order to increase the blocking force during assembly, some grippers enable also to freeze the droplet (Kochan 1997; Lopez-Walle et al. 2008).

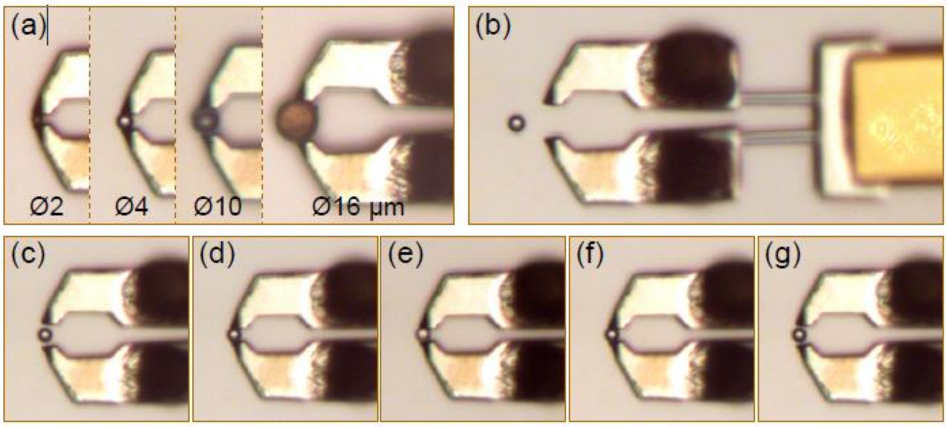

Fig 2. Example of a magnetic actuated microtweezer grasping Polystyrene (PS) microbeads with diameter of 2, 4, 10, and 16 µm (a), demonstrating a pick-and-place operation of a PS microbead with diameter 4µm (b)-(g) (Xie et al. 2020).

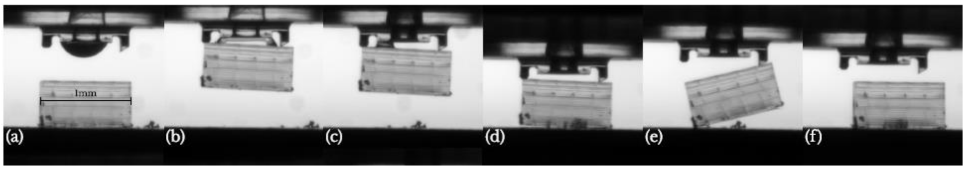

Fig 3. Example of capillary-based gripper enabling to pick up and release of a sub-millimeter object (Dehaeck et al. 2019).

Non contact micromanipulation

As adhesion strongly disturbs the release in contact manipulation, another way has been explored, consisting in moving an object with remote forces (magnetic force, electrostatic force, etc.). These approaches are named “non-contact micromanipulation”. In this case, the trajectory is not disturbed by adhesion but the blocking force is weak. Moreover, the forces are usually non-linear with respect to the position and to the control parameter (e.g. actuation force is a quadratic function of the voltage in dielectrophoresis). Consequently, non-contact manipulations require non-linear controllers.

Magnetic micro-nanomanipulation: Magnetic forces are widely used to control the trajectory of micro-nano-objects. Indeed, it is possible to generate a significant force on a micro-nano-object placed several centimeters far from the magnetic field source. The trajectory of the object can thus be controlled in a remote way through the control of the magnetic field. A lot of configurations of magnetic sources (permanent magnets, planar coils, Helmhotz coils, electromagnets, etc.) and type of micro-objects are possible in the micro-nano-world (Cugat et al. 2003). The controlled magnetic field is usually generated by coils, electromagnets or by moving permanent magnets. The manipulated objects have to be sensible to magnetic field: ferromagnetic micro-objects but also diamagnetic and paramagnetic objects are considered. The ferromagnetic objects induce larger forces but the remanent magnetization induces aggregates of micro-objects. The diamagnetic and paramagnetic objects experiment lower forces but have no remanent magnetization. The object movement can be induced (i) directly by the magnetic force and torque applied by the magnetic field on the object (see fig. 4) (Hu et al. 2018) or (ii) indirectly using helical movement or swimming movement in liquids (Barbot et al. 2018). Various applications, actuation principles and control methods are described in (Xu et al. 2015).

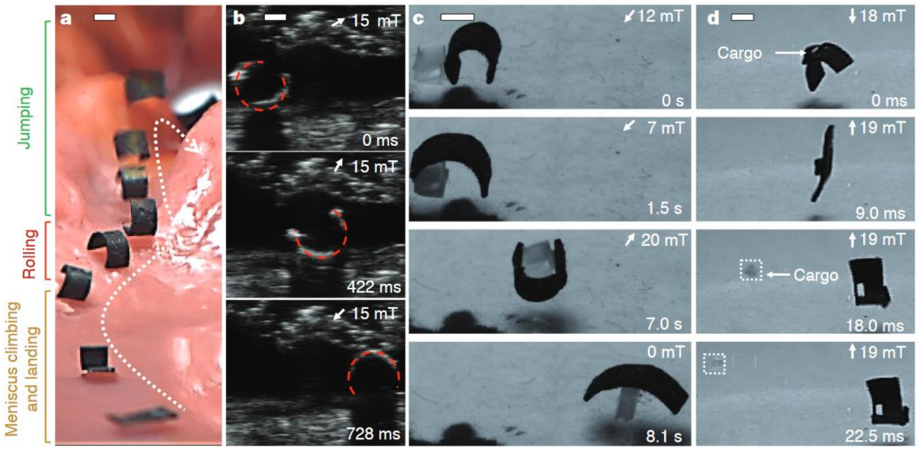

Fig 4. Example of a micro-object (microrobot) manipulated using magnetic force and torque (Hu et al. 2018).

Dielectrophoresis: The electrostatic effects can also be used to manipulate micro-nano-objects. The most used principle is the “dielectrophoresis” which appears when a dielectric object is placed in a non-uniform alternative electric field (Pohl and Crane, 1971). This effect is used to move objects in liquids and particularly in microfluidic channels. The electric field is controlled via the voltages applied on electrodes inside the microchannel. As the deposition of microelectrodes is one of the basic process in microelectronics and MEMS fabrication, this method is fully compatible with the clean room microfabrication constraints. The application range of the force is low (above 100 micrometers far from the electrodes, the dielectrophoresis force is usually lower than the weight of the object) and the electrodes have to be close to the object. Moreover, the applied force is usually lower than that used in the magnetic micromanipulation. This method enables to control the trajectory of the particle (Kharboutly and Gauthier 2013) and also its orientation (Michalek 2019).

Optical tweezers: The optical tweezers enable to manipulate micro-objects with light. Under certain conditions, it is possible to show that a micro-nano-object will be trapped in the center of a laser beam (Ashkin et al. 1987): moving the laser beam enables to move the trapped micro-nano-object. The advantages of this method is the selectivity, the laser applies a force only on the micro-nano-object placed in the beam; the surrounding objects do not move. However, the force is lower than the one used in magnetic micromanipulation and dielectrophoresis. Optical tweezers are able to manipulate multiple micro-objects independently using a simple laser (Arai et al. 2004) or using Holographic methods (Memmolo 2015). It also enables to manipulate swimming microrobots (see fig.5) (Gerena et al., 2019).

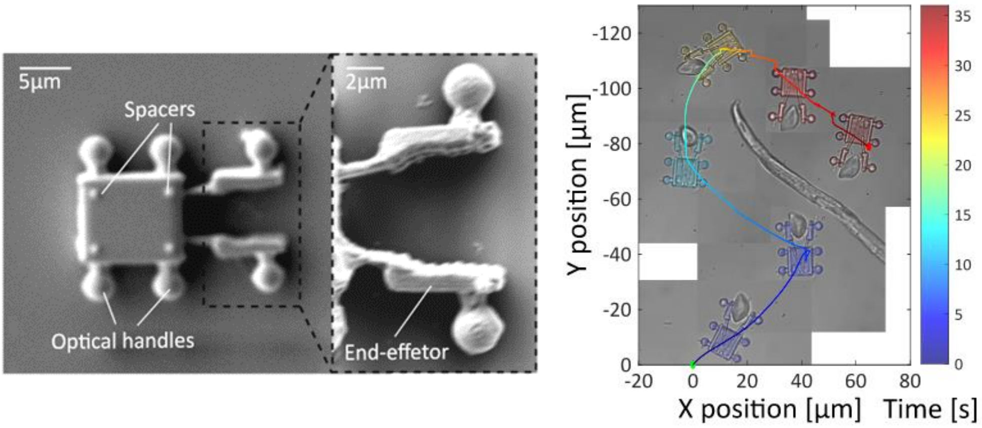

Fig 5. Example of microrobot manipulated using laser trapping (Gerena et al. 2019).

Fluidic and acoustic methods: Some applications (e.g. biological cell positioning) require manipulating micro-nano-objects in liquids. In that case, the movement of fluid or the acoustic pressure can be used to position or sort micro-nano-objects. The fluid movement in microchannel is a relevant way to move particles along a long range (Zhang et al. 2016). Locally, acoustic pressure controlled by oscillators placed around the channel is able to position precisely micro-nano-objects (Ding et al. 2012; Baudoin and Thomas, 2019). Various original ways exist to control the fluid flows including thermocapillary convection enabling to control the trajectory of micro-nano-objects placed on an air/liquid interface (Terrazas et al. 2018).

Examples of applications

Micro-nano-manipulation technologies address three major application fields:
- the industrial micro-nano-assembly enabling to build innovative highly miniaturized assembled products;
- the scientific instrumentation requiring the positioning of micro-samples for local analysis;
- the biomedical field in which single biological cells positioning and characterization are becoming a huge challenge.

Industrial micro-nano-assembly:

The global trend in industry is to reduce the size of the products in order to improve their efficiency and to preserve natural resources. Indeed, usually energy consumption is reduced when reducing the size of a system and the amount of materials required to build it is also reduced. The robotic micro-nano-assembly is one way to produce highly miniaturized products combining micro-components (Gauthier et al. 2015; Cecil et al. 2016). It concerns a large variety of final markets. The most common application is the fabrication of the electronic SMD components made by die bonding machine. Micro-optical components (sensors and telecommunication markets) require also to combine a large variety of components and will benefit from robotic micro-nano-assembly (Caspar et al. 2018). At the nanoscale, some principles of advanced sensors and detectors have been proposed in the literature in which the fabrication is still a challenge. Robotic micro-nano-assembly offers an opportunity to produce nanosensors in a reliable and efficient way (Rauch et al. 2018).

Scientific instrumentation:

Positioning, in a precise manner, micro-nano-object has also some interest in scientific instrumentation. The best example is the analysis of mechanical behavior of natural fibers, which is a key scientific issue for the development of biomaterials. Micro-nano-manipulators are used to grasp natural fibers in order to test their mechanical behavior (Latifi et al. 2015). Moreover, the robotic micro-assembly (see above) enables to produce new scientific instruments and/or microprobes (Gauthier et al. 2015).

Biotechnology:

As a biological cell has a characteristic size between few micrometers to hundreds of micrometers, their positioning is in the field of micro-nano-manipulation. Several application frameworks exist in single cell positioning and the reader can report to review papers in this field for more information (Eylan et al. 2017; Xu et al., 2018). Some works are dedicated to oocytes (the largest non-adherent cell) positioning and testing (Gana et al. 2017). Blood cells positioning and sorting are also investigated (Li et al 2018). Advanced works are dedicated to single cell surgery (Shakoor et al. 2019).

Future Directions for research

Despite the strong advances of methods and technologies in Micro-nano-manipulation since 1990, the robotic functions in micro-nano-world do not reach currently the level of performances obtained in macro-scale robotics. It opens the way to large perspectives in term of research and developments.

The adaptability and the autonomy of the robotic micro-nano-manipulator are key challenges for the future. Indeed the physical effects predominant in micro-nano-world (e.g. adhesion) are highly dependent of surface properties (e.g. level of oxidation) and of environmental parameters (e.g. humidity) and are thus difficult to predict and vary significantly along time. The adaptability of the robot is thus essential to reach its autonomy. It requires to integrate more sensors on micro-nano-manipulators such as force sensors and also to improve the robot dexterity (Gauthier et al. 2015). Micro-nano-manipulators will include more and more artificial intelligence to learn by demonstration and/or online how to adapt their behavior when the physical parameters are changing. However, one of the main problems of artificial intelligence for small-scale learning is related to the lack of databases and the fact that the construction of databases is complex.

The performances of the micro-nano-manipulator have also to be pushed forward to smaller scale. Some proof of concept of nanoscale manipulations have been proposed in the literature, but the efficiency and reliability need to be significantly improved. Nanoscale assembly or characterization require to better understand the predominant physical effects in nanoscale in order to improve the reliability of the nano-manipulators. Nanoscale manipulation will also take benefit of the new tridimensional printing capability enabling to design and build fully tridimensional objects and/or end-effectors.

The current trend is also to merge mobile microrobotics and micro-nano-manipulation in order to provide mobile microrobots having the ability to grasp micro-nano-objects (see example in fig. 1, 3, 4 above). It requires to use controllable remote actuation to power independently (i) the locomotion of the micro-robots and (ii) the gripper actuator. It will enable to perform microhandling in confined space: microchannel for biomedical applications or Scanning Electron Microscope (SEM) for nanoscale applications. It also will enable to provide small-scale collaborative robotics to study emerging collective behavior comparable to collective insects.

The technologies developed in micro-nano-manipulation contribute to micro-nano-mechatronics and miniaturized robotics in general. Typically, the remote actuation principles and modeling (e.g. magnetic actuation) developed in micro-nano-manipulation can be applied for remote actuation of robotic microneedle in microsurgery. The actuation principle of grippers can be used for micromechatronic system actuation in wider application frames.

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