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A micromanipulation cell including a tool changer

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Abstract
This paper deals with the design, fabrication and characterization of a tool changer for micromanipulation cells. This tool changer is part of a manipulation cell including a three linear axes robot and a piezoelectric microgripper. All these parts are designed to perform micromanipulation tasks in confined spaces such as a microfactory or in the chamber of a scanning electron microscope (SEM). The tool changer principle is to fix a pair of tools (i.e. the gripper tips) either on the tips of the microgripper actuator (piezoceramic bulk) or on a tool magazine. The temperature control of a thermal glue enables one to fix or release this pair of tools. Liquefaction and solidification are generated by surface mounted device (SMD) resistances fixed on the surface of the actuator or magazine. Based on this principle, the tool changer can be adapted to other kinds of micromanipulation cells. Hundreds of automatic tool exchanges were performed with a maximum positioning error between two consecutive tool exchanges of 3.2 μm, 2.3 μm and 2.8 μm on the X, Y and Z axes respectively (Z refers to the vertical axis). Finally, temperature measurements achieved under atmospheric pressure and in a vacuum environment and pressure measurements confirm the possibility of using this device in the air as well as in a SEM.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Today, most manufactured micromechanisms are assembled either manually or with macrosized, expensive and dedicated machines. Improving the flexibility, and decreasing the costs and the operator's fatigue are quite challenging. Indeed, problems such as adhesion, size, precision, actuation and sensing (notably force and vision) are specific to microassembly [1–3].

Recent research allowed the development of flexible cells [4–7] able to work automatically in confined spaces [8–12]. Nowadays, two main fields are making significant progress:

- the micromanipulation in a SEM (mainly pick and place tasks) [12, 13] contributes to the effectiveness of the mechanical study of material samples in the SEM (nanoscratching, nanoindentation and structural study);
- in a microfactory, sequences of elementary micromanipulation tasks (pick, move, rotate, place, fix, assemble, . . .) of objects from a few micrometers to several millimeters in size are performed in confined spaces (in the range of several cubic decimeters) [14, 15].

Flexibility gives great benefit to micromanipulation cells [16, 17]. To increase the flexibility of a micromanipulation cell and its effectiveness to work in confined spaces, a tool changer has been developed at the Laboratoire d'Automatique de Besançon (LAB). This system enables one to choose a suitable pair of tools (shape, gap between both tools and roughness) according to the properties of the manipulated objects (shape, size, material).

At the moment, very few devices including a tool changer are adapted to the microworld. The known solutions are closer to a miniaturization approach [12, 18] with, for example, a

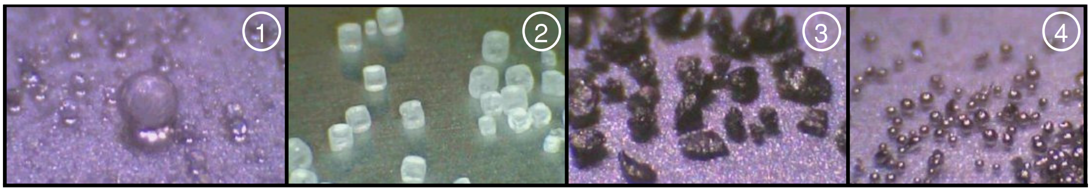


Figure 1. Manipulated objects: (1) glass spheres (diameter from 1 to 1000 μm), (2) grains of fine salt (cubes of 70–600 μm), (3) grains of NiCBSi (about 300 μm in diameter), (4) titanium spheres (diameter from 50 to 200 μm).

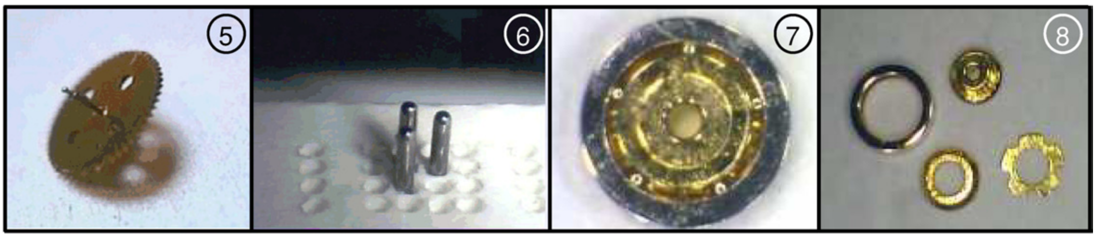


Figure 2. Mechanisms for assembly tasks testing: (5) watch microgear (cross-section axis diameter: 140 μm), (6) pins 300 μm in diameter, (7) bearing 1.6 mm in diameter and balls of 200 μm,[1] (8) parts of this bearing.

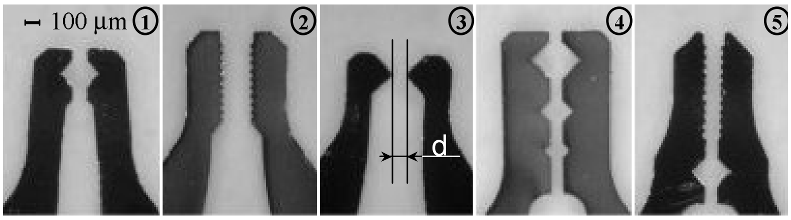


Figure 3. Different kind of pairs of available tools. *d* is the initial gap between both tools (i.e. without gripper's actuation). These tools are made of nickel with a thickness of 200 μm. The scale is the same for all pictures.

revolver turret [19, 20], than really dedicated to the microworld [21, 22]. To present our tool changer, its usefulness will be discussed in section 2. The action principle will be explained in section 3 and its characterization will be detailed in section 4. Finally, examples of micromanipulation tasks will be described in section 5.

2. The usefulness of a tool changer

We are currently working on the manipulation of several kinds of micro-objects (from 20 to 500 μm in size) with a microgripper in confined spaces (microfactory or SEM). For example, figure 1 shows cubic grains of table salt, glass spheres, grains of metallic alloys and titanium spheres. In addition to microworld modeling, manipulating these micro-objects is necessary to study the influence of the shape, size and material of the objects on micromanipulation problems. The specific problems of microassembly are studied through the assembly of manufactured mechanisms (figure 2). Pick and place, rotation and insertion tasks of these objects can be performed under different environmental conditions such as

- dry environments (air),
- liquid environments (water or biological liquids),
- low pressure environments (SEM for example).

[1] These bearings are manufactured by MPS Micro Precision Systems AG in Switzerland, http://www.mpsag.com.

All these objects can be classified according to their shape, size and consistency. Different kinds of tools have been specially designed to be well adapted to the manipulation of these different classes of objects. These tools are made of nickel using a LIGA-UV process. Figure 3 shows some examples of the available pairs of tools. The characteristics of the manipulated objects (shape, size and material) influence the choice of the tools. The characteristics of the tools that can be chosen here are

- the shape of the tool's tip (that will be in contact with the object),
- the initial gap *d* between both tools (figure 3),
- the roughness and the surface of contact between tools and object (to decrease adhesion problems: tools 2 and 3 of figure 3).

2.1. The microgripper

A pair of tools must be fixed at the tip of the actuator. The actuator and a pair of tools connected together is called the *microgripper* in this paper (figure 4). The actuator uses a double piezoelectric bimorph combining an in-plane (*Y* axis) and an out-of-plane motion (*Z* axis). Figure 5 displays the working principle of this actuator.

The four degrees of freedom (DOF, two per finger) of the gripper are useful to perform insertion or rotation tasks. They also permit correction of a possible misalignment of the tools.

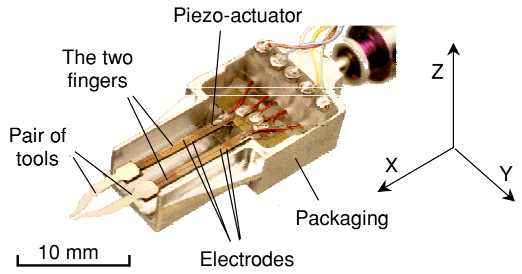


Figure 4. Picture of the microgripper.

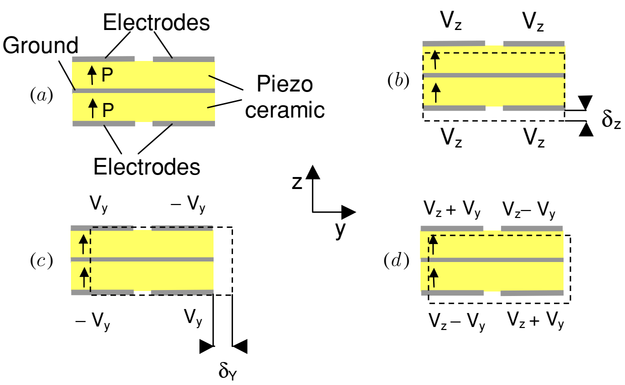


Figure 5. Cross section of a gripper finger (*Y*–*Z* plane): working principle of the actuator. (*a*) Structure, *P* indicates the direction of polarization, (*b*) V_Z generates a displacement along the *Z* axis (δ_Z), (*c*) V_Y and V_Z generate a displacement along the *Y* axis (δ_Y), (*d*) the combination $V_Y + V_Z$ and $V_Y - V_Z$ can generate simultaneous displacements along the *Y* and *Z* axes.

Table 1. Characteristics of the four degrees of freedom (i.e. two per finger) microgripper. Strokes are given for a ±100 V supply voltage.

	Y	*Z*
Stroke per finger	±80 μm	±200 μm
Blocking forces	55 mN	10 mN
First resonance frequency	1000 Hz	400 Hz

The characteristics of the gripper are reported in table 1. More details are given in [23] and [24].

2.2. The micromanipulation cell

To perform micromanipulation tasks, the gripper can be fixed on a manipulator. We currently use two kinds of manipulators. Both have three axes. The first one is composed of a three linear axes manipulator from the Physik Instrumente (PI) company (figure 6). The resulting micromanipulation cell is used for current micromanipulation tasks and measurements. Each axis is actuated by a servo dc motor. It allows 25 mm of stroke in the *X*, *Y* and *Z* directions with a unilateral repeatability of 0.1 μm and a backlash of 2 μm.

A user interface has been developed using Borland Builder C++ to control the micromanipulation cell (3 DOF of the manipulator, 4 DOF of the gripper and the tool changer that will be presented in section 3) through a joystick. Figure 7 reports the diagram of this micromanipulation cell.

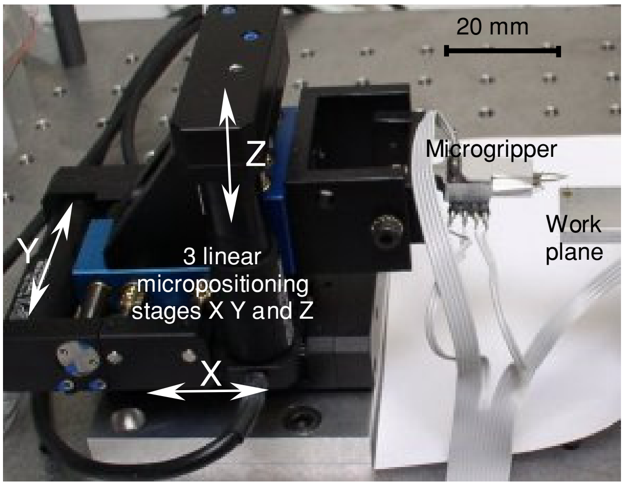


Figure 6. Current micromanipulation cell: diagram of the microgripper fixed on the three axes (translations *X*, *Y* and *Z*) robot.

For the manipulations in a SEM, the microgripper can be fixed on the MM3A manipulator that is actuated with piezoelectric motors and that is very compact (figure 8)[2].

Depending on the application, it is possible to use other kinds of manipulators (micropositioner described in [25] for example).

2.3. Solutions to improve the flexibility of the micromanipulation cell

Several solutions to improve the flexibility were studied to realize automatic and flexible manipulation and assembly tasks in confined spaces:

- using several micromanipulation cells, each of them dedicated to one elementary task. In this case, as many micromanipulation cells as elementary tasks are required. This solution is costly and requires more space and control complexity.
- reducing the required space and the complexity of the controls by using only one manipulation robot and changing only the grippers. Each gripper would be dedicated to one elementary task. This solution is better than the first one but, because of the ratio between the size of one gripper and the stroke of the robot axes, this solution would require the use of a robot with larger strokes (and consequently a bigger robot). Indeed in the case of an automatic assembly process, the workspace of the cell is not large enough to allow automatic tool exchanges with more than two grippers. So, this strategy is not optimal.
- changing only the gripper tools (i.e. the tips of the gripper). This solution is cheaper because all the expensive parts (robot and gripper actuators) are kept during the whole assembly process. A large saving of space is also possible using this solution. In this way, our strategy consists in the use of a magazine and the development of a solution to fix a pair of tools either on the tip of the actuator or on the magazine (figures 9(*a*) and (*b*) respectively).

[2] From Kleindiek Nanotechnik GmbH, Aspenhaustrasse 25, 72770 Reutlingen, Germany. http://www.nanotechnik.com.

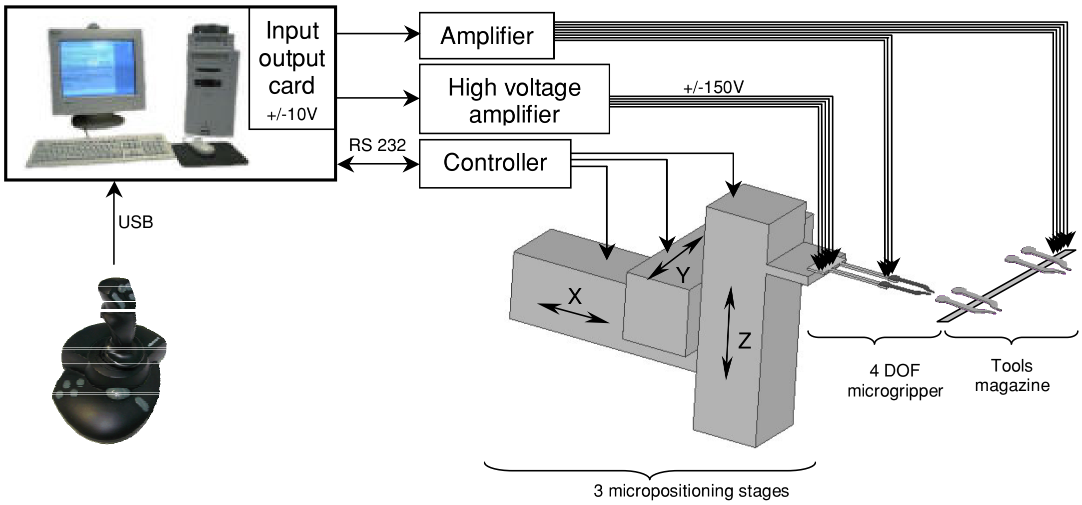


Figure 7. Diagram of the micromanipulation cell composed of three linear micropositioning stages, a microgripper and a tool changer.

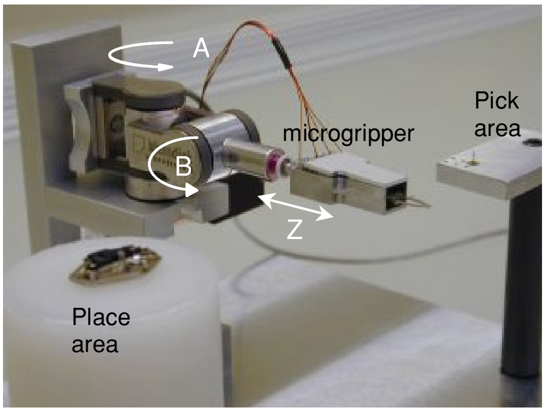


Figure 8. Micromanipulation cell for manipulation in a SEM: microgripper fixed on the three axes (rotation A-rotation B-translation Z) MM3A robot.

3. The tool changer

The tool changer enables one to perform efficient micromanipulation tasks. Indeed, it is possible to choose the suitable pair of tools according to the properties of the manipulated object (shape, size, material). Adhesion problems can also be taken into account through the choice of the roughness and surface of contact between tool and object.

3.1. Action principle of the tool changer

The solution developed to exchange tools is based on a thermal glue. This glue[3] is liquid at 65 °C and solid at room temperature. Hundreds of solidification and liquefaction cycles are possible without spoiling the mechanical properties of the glue. A small amount of this glue (about 4 nL per contact) is placed at the contact between the actuator tips and the tools and also at the contact between the magazine and the tools (figure 10). Surface mounted device (SMD) resistances are fixed under these two contacts. One resistance of 6 Ω is used for each contact. When an electrical energy is supplied to these resistances, they heat up by the Joule effect, liquefying the glue at the corresponding contact points. When the supply is switched off, the temperature of the resistances decreases and the glue solidifies. Then, it is possible to fix one pair of tools either on the tip of the actuator to perform a micromanipulation task (figure 9(*a*)) or on the magazine to exchange the pair of tools (figure 9(*b*)).

One of the biggest interests of this solution consists in the fact that very low contact forces are required to fix the pair of tools on the tip of the actuator or on the magazine. It is also very appreciable that we only need to supply the resistances to liquefy the glue during a tool exchange, i.e. twice per cycle.

Figure 11 details the operating cycle for the exchange of a pair of tools. This example shows how to pick and place a microgear (elementary task 2) after having stacked cubic parts (elementary task 1). The axis diameter of the manipulated microgear is 140 μm. This operation requires the use of the pair of tools no 1 as numbered in figure 3. The 200 μm cubic parts are stacked using the pair of tools no 2 (see figure 3).

3.2. Adjustment of the tool changer

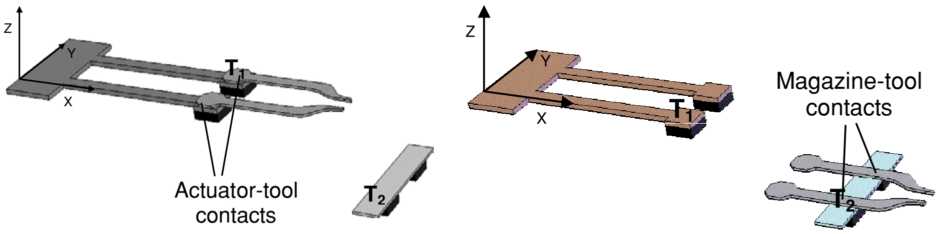
To perform an efficient tool exchange, several parameters must be adjusted. The parameters that influence the tool exchange reliability and repeatability the most are

- electrical current value and duration of the resistances supply,
- approach trajectories and speeds during the deposition phase of a pair of tools.

When the use of a new pair of tools is required, the relative position between the two tools, their relative orientation with the gripper actuator and the magazine must be adjusted. The initial position of the pair of tools in the magazine is then stored. This information is used each time we need these tools.

We use nickel tools, so they have a high thermal conductivity. Thus, when the resistances under the contact

[3] Reference Crystalbond 555-HMP, from Crystalbond™ series made by Aremco Products, Inc. (USA).



(*a*) (*b*)

Figure 9. Diagram of the actuator–tools–magazine–resistances set: (*a*) the pair of tools is fixed at the tip of the actuator (manipulation configuration); (*b*) the pair of tools is fixed on the magazine (configuration of tool exchange).

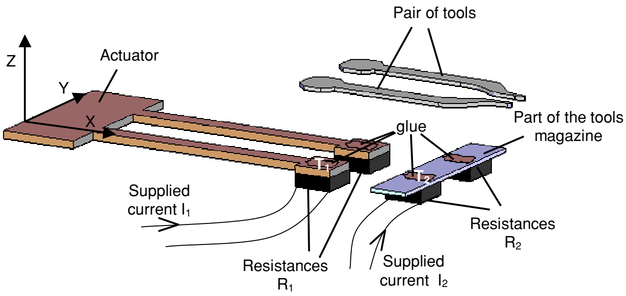


Figure 10. Diagram of the actuator–tools–magazine–resistances–glue set. Small amounts of glue are placed at the future contacts actuator–tools and tools–magazine.

between the actuator and the tools (R_1 in figure 10) are supplied (I_1), the glue at the contact between the tools and the actuator liquefies but, by conduction, the glue between the tools and the magazine is also heated up. So, if the supplied current I_1 is too high or too long, the glue at the contact between the tools and the magazine could become soft or even liquefy. Therefore, a thermal study is necessary to determine precisely the power to apply to the resistances and the duration of this supply. The full study and the comparison of conduction, convection and radiation phenomena in air and vacuum environments have been conducted but as they go beyond the scope of this paper, they will be detailed in further publications.

Classical differential scanning calorimetry measurements were used to determine that the melting process of the glue starts at 49 °C and that the glue is totally liquid at 62 °C in the air.

According to this, simulations and measurements have been carried out to determine the required intensity and the duration of the current. One tool was fixed at the tip of the actuator and on the magazine at the same time (configuration of image 2, figure 11). Two thermocouples were used and fixed on this tool. The first one was placed to measure the temperature at the contact between the actuator and the tool T_1 (figure 9(*a*)), the second one at the contact between the tool and the magazine T_2 (figure 9(*b*)). The diameter of the thermocouples (25 μm) is very small compared to the size of the tools (approximately $10 \times 1 \times 0.2$ mm^3), so the influence of the thermocouples wires was neglected. Figure 12 shows these measurements for a supplied current of 164 mA during 60 s. This case corresponds to a good compromise. Using these values, it is necessary to supply this current during 35 s before the total liquefaction. These measurements also show that 15 s are necessary before the total solidification of the glue. These values have been used for all the other measurements.

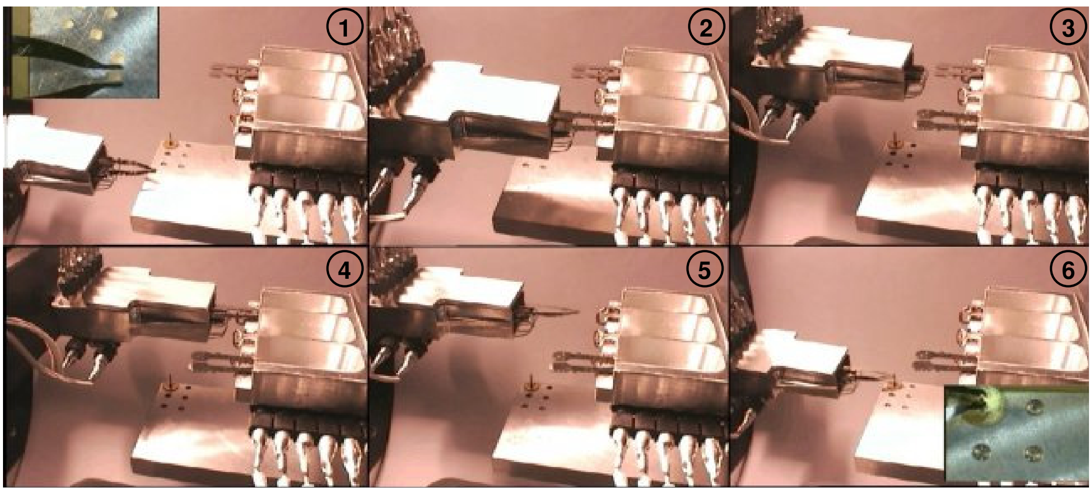


Figure 11. Successive steps for exchanging a pair of tools: (1) manipulation of a cubic part with 300 μm size using the first pair of tools, (2) release of the first pair of tools in the magazine by firstly solidifying the glue at the contacts actuator–tools and secondly by liquefying the glue at the contacts tools–magazine, (3) the actuator alone reaches the position of the second pair of tools, (4) solidification of the glue at the contacts between the actuator and the tools and then, liquefaction of the glue at the contacts between the tools and the magazine, (5) motion of the gripper: the second pair of tools is fixed at the tip of the actuator, (6) manipulation of a gear 140 μm in axis diameter.

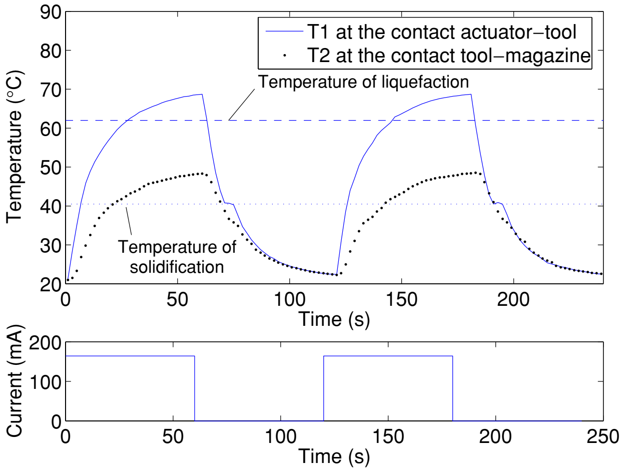


Figure 12. Measured temperatures T1 at the actuator–tool contact and T2 at the tool–magazine contact for a supplied current of 164 mA.

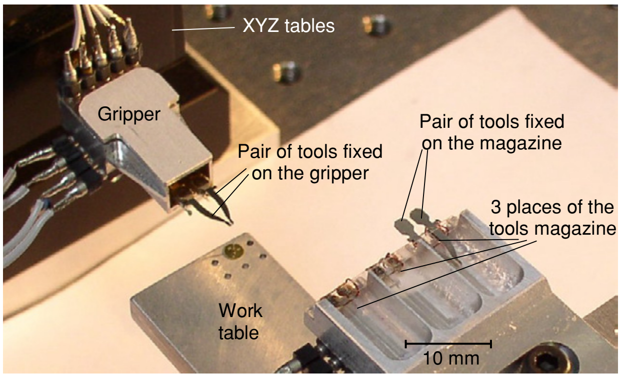


Figure 13. Close view of the magazine.

3.3. Solutions to improve the tool changer

Several ideas were developed to improve the flexibility of the tool changer. For example, the resistances of the central place of the magazine (figure 13) can be supplied separately. As both resistances of the gripper can also be supplied separately, by combination, it is possible to adjust the initial gap d between two tools (figure 3). This technique helps reduce the number of pairs of tools that can be placed in the magazine. For example, with this system, one pair of tools is enough to manipulate cubic parts of all sizes from 20 to 500 μm. The only operation to do is the change of the initial gap when necessary using this central place of the magazine. Without this system, due to the stroke of the gripper (320 μm maximum), two pairs of tools would have been necessary (i.e. tools with the same shape but with a different initial gap). Of course, the length of the tools also influences the maximum stroke available.

Finally, the magazine has been designed as a first module for three pairs of tools. If more than three pairs of tools are needed, it is possible to stack several of these modules.

4. Characterization of the tool changer

Once having established the tool exchange principle and the adjustment of the most important parameters, it is possible to characterize precisely the tool changer. In this aim, measurements of the tools positioning accuracy were conducted, then the mechanical characteristics of the glue film and the SEM compatibility of the system were studied.

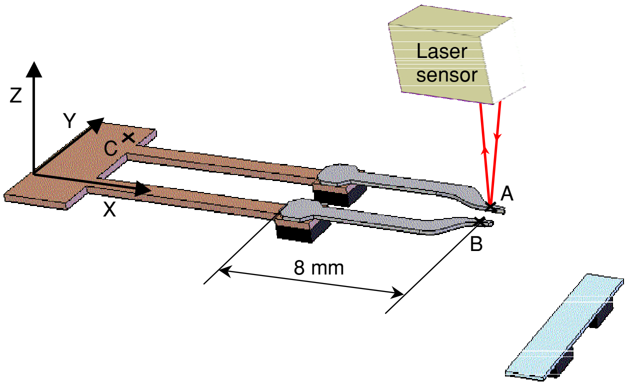


Figure 14. The positioning measurement set-up. Example given for measurements on the Z axis. A (tool 1), B (tool 2) and C (reference) are the initial positions of the measured points.

4.1. Tool positioning accuracy

When a pair of tools is used several times, the positioning of these tools is not perfect, mainly because of the mechanical strengths and thermal conduction during a tool exchange (thermal expansion of the tools is insignificant). For this reason, we have studied the tool positioning accuracy between two tool exchanges. To validate the principle of this device, this accuracy must be compatible with the precision necessary for the micromanipulation tasks and with the size of the manipulated objects. To characterize the tool positioning accuracy, the micromanipulation cell shown in figure 7 was used. This system enables one to perform automatically hundreds of cycles of tool exchanges including measurements of tools position. A laser sensor[4] with a resolution of 100 nm (based on a classical triangulation principle) was used to measure the relative position of the tools (figure 14). The test cycle is defined by the following sequence:

- position measurement at the tip of one tool (point A on figure 14 for Z axis measurements),
- translation to place the second tool under the laser beam,
- position measurement at the tip of the second tool (point B),
- translation to place a non-actuated part of the actuator under the laser beam,
- position measurement of the position of this point that will be used as reference (point C),
- translations to reach the position where we release the tools in the magazine,
- deposition of the tools in the magazine,
- translations of the actuator alone,
- translations of the actuator to reach the position for exchanging the tools,
- removal of the tools from the magazine.

This cycle has been automatically repeated hundreds of times to measure the tool positioning accuracy on the X, Y

[4] LC-2420W from the KEYENCE company.

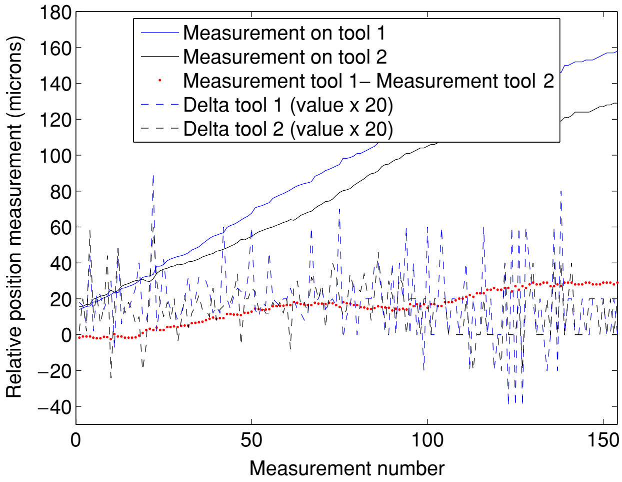


Figure 15. Measurements of the relative positioning accuracy between two consecutive tool exchanges on the X axis. Delta (δ) tools 1 and 2 are the maximum displacements possible between two consecutive tool exchanges on tools 1 and 2 (difference of two consecutive measurements).

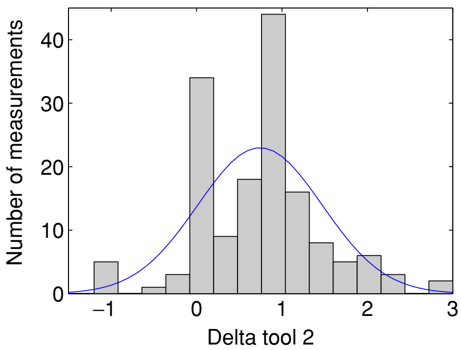


Figure 16. Distribution of the maximum displacement possible between two consecutive tool exchanges on the X axis (example given for tool 2 shown in figure 3).

and Z axes. Figures 15 and 18 display the results on the X and Z axes respectively. More details concerning these measurements are given in [26]. δ is the difference of the measured position between two consecutive tool exchanges. Thus, the maximum positioning error of the tip of the tools between two consecutive tools exchanges is 3.2 μm, 2.3 μm, 2.8 μm on the X, Y and Z axes respectively. The average of this error is about 1 μm for each axis. The histograms of the previous measurements are displayed in figures 16, 17 and 19. The results are close to Gaussian distributions. The standard deviations are 0.73, 0.47 and 1.16 μm and the averages are 0.74, 0.62 and 0.03 μm along the X, Y and Z axes respectively. The causes of this deviation have not yet been precisely established but it is possible to correct the position of the tools either by using the middle part of the magazine or the out-of-plane motions of the gripper.

4.2. Mechanical performances of the thermal glue film

Mechanical tests have been performed to characterize the performances of the glue film. Measurements were conducted to determine that 300 mN can be applied at the tip of a

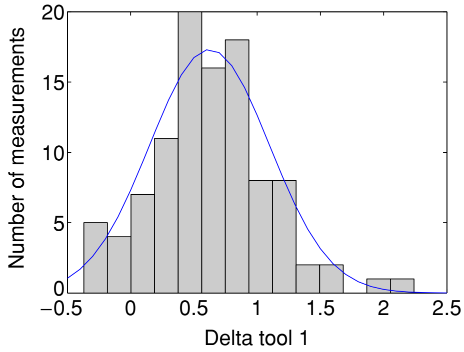


Figure 17. Distribution of the maximum displacement possible between two consecutive tool exchanges on the Y axis.

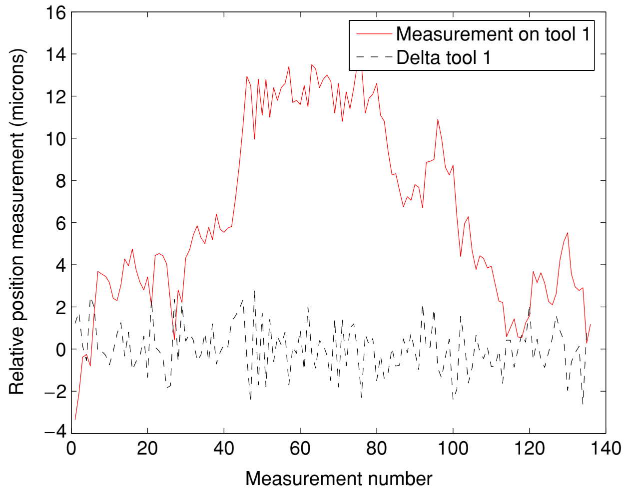


Figure 18. Measurements of the relative positioning accuracy between two consecutive tool exchanges on the Z axis. Delta tool 1 is the maximum displacement possible between two consecutive tool exchanges on tool 1 (difference between two consecutive measurements).

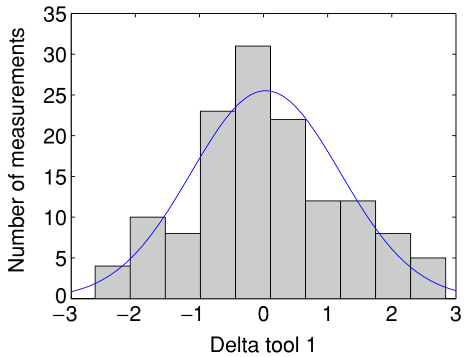


Figure 19. Distribution of the maximum displacement possible between two consecutive tool exchanges on the Z axis.

tool (along the Y axis) before breaking the film of thermal glue between actuator and tool. This value is on one hand lower than the force that can be applied before breaking the piezoactuator (400 mN) and on the other hand higher than the maximal blocking force during the manipulation (110 mN). Consequently, the mechanical strength of the glue film allows

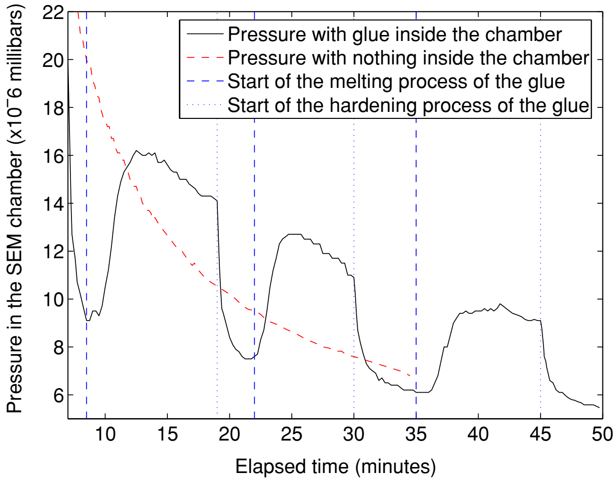


Figure 20. Pressure variation versus time when a part of glue is successively liquefied and solidified several times inside the SEM. These measurements can be compared to the pressure variation versus time given when there is nothing inside the SEM (reference).

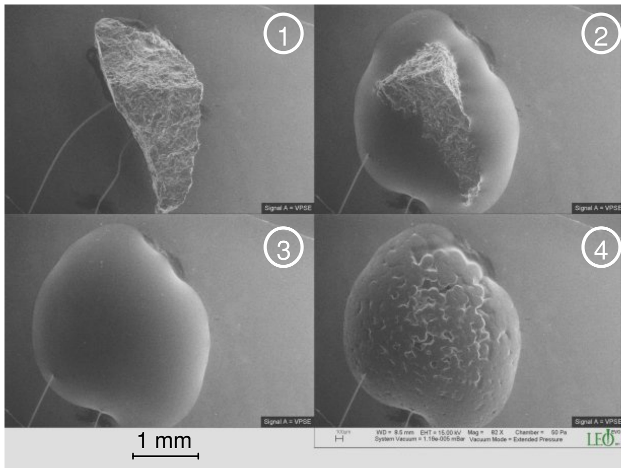


Figure 21. Study of the temperatures of liquefaction and solidification of the thermal glue in a vacuum environment (SEM): (1) part of solid glue (the thermal glue is bought under bar packaging and can be broken in little parts), (2) start of the liquefaction of this part of glue, (3) the glue is totally liquefied, (4) the glue is totally solidified again. A second liquefaction of the glue would give the result given in picture 3.

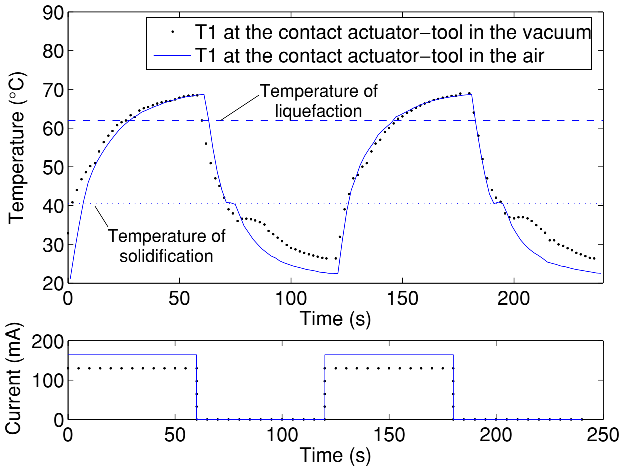


Figure 22. Influence of the environment (ambient air or vacuum) on the temperature evolution versus time at the contact between the actuator and the tool. Thermal measurements in the air and in a SEM of a part of thermal glue undergoing liquefaction–solidification cycles.

us to perform safety micromanipulation tasks. It behaves like a safety fuse in case of motion error or default.

4.3. SEM compatibility

As mentioned before, performing micromanipulation tasks inside a SEM or TEM chamber presents lots of interest notably for material testing and characterization at the microscale. Unfortunately, these chambers are quite small. Moreover, if a sequence of elementary micromanipulation tasks must be performed, several kinds of pairs of tools are required. Making a micromanipulation task needing another pair of tools than the one used inside the chamber currently requires the following procedure:

- switch off the emission of electrons,
- increase the pressure inside the chamber to reach the atmospheric pressure,
- open the door,
- change the gripper manually (without breaking it),
- set up the position of the gripper,
- close the door,
- pump up to reach the minimal pressure allowing the electron beam to be switched on,
- switch on the emission of electrons,
- adjust all the parameters (amplification, . . .) for a good visualization.

Using this way, the sequence to exchange the gripper requires between 10 and 30 min and a new calibration of the gripper is necessary. For these reasons, it could be extremely interesting to be able to use the tool changer inside a SEM. Nevertheless, during a tool exchange, the liquefaction of the glue generates gas that can modify the pressure inside the SEM chamber. Pressure measurements have been done to study the degassing process of the thermal glue during liquefaction–solidification cycles inside the SEM. A high vacuum SEM was used to perform these measurements. This kind of SEM displays images only of metal or metallic samples. The pressure must remain lower than 1.5×10^{-5} millibars to allow a good working of the electron beam. The quality of the images gets better when the pressure inside the chamber of the SEM decreases. For this reason, the environment inside the chamber is continuously pumped. Thus, to be used as reference, a measurement has been done without anything inside the chamber. Then, resistances have been placed inside the chamber with a large amount of thermal glue over them (about four times more than usually needed for a tool exchange). The pressure inside the chamber was measured during solidification and liquefaction cycles. Figure 20 displays the results of pressure evolution versus time inside the vacuum chamber. These measurements showed that there is a degassing process but it is low enough to provide a usual working of the electron beam.

Finally, we must note that if conduction and convection are the essential thermal phenomena in the air, conduction and

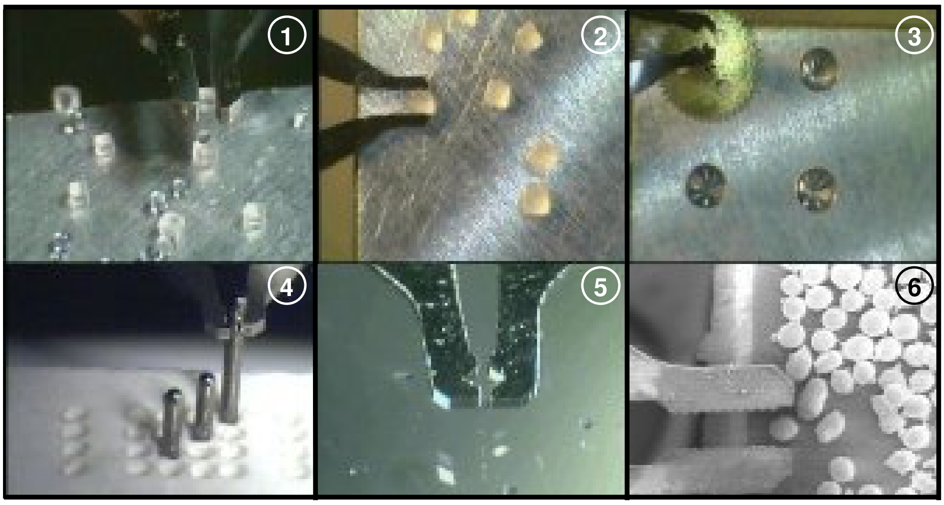


Figure 23. Examples of elementary micromanipulation tasks: (1) stacking of 200 μm cubes and spheres, (2) pick and place, stacking cubic parts of 300 μm, (3) pick and insertion of a watch gear whose axis measures 140 μm in diameter, (4) matrix of 300 μm diameter pins, (5) manipulation of 120 and 50 μm diameter spheres in a liquid environment, (6) manipulation of 200 μm grains inside a SEM.

radiation are predominant in the vacuum. Because of that, thermal measurements have been done inside a SEM chamber firstly in order to determine the temperatures of liquefaction and solidification of the glue in a vacuum environment (60 °C and 37 °C respectively, figure 21) and secondly to compare the temperature evolution in the air and in the vacuum. To perform these tests, a variable pressure SEM was used. The pressure inside this kind of SEM is controlled by the addition of gas. This gas catches the electrons that are accumulated on the surface of non-metallic samples. So, this kind of SEM also allows us to visualize non-metallic samples. Thermocouples have been placed in a part of glue inside the chamber of the SEM allowing temperature measurements. In the vacuum environment, only the temperature at the contact between the actuator and the tools was measured. A supplied current of 164 mA in the air is necessary to reach 68 °C whereas only 130 mA is enough in the vacuum. Figure 22 shows that the evolution of the temperature versus time in the vacuum and in the air are close. Obviously they are not obtained for the same supplied current.

These measurements show that the tool changer can be used in a SEM environment. In the near future, total functioning of the tool changer will be fully tested in a SEM.

5. Examples of micromanipulation tasks

The typical dimensions of manipulated objects (gear, parts of bearings, parts of MOEMS, spheres, pins, lenses, cubes, grains, . . .) are here between 20 and 500 μm. These objects have very different characteristics. It is possible to perform these micromanipulation tasks in different environments such as air, liquid, biological environment and vacuum (figure 23). Manipulating in a liquid environment can be interesting because adhesion forces are significantly reduced and hydrodynamic forces give rise to damping that limits loss of objects during manipulation tasks [27]. Finally, it is also possible to make a sequence of elementary micromanipulation tasks to perform a full assembly process.

6. Conclusion

Micromanipulation cells have been developed to permit automatic and flexible assembly tasks of micro-objects in confined spaces such as a microfactory or a SEM chamber. They include a three axes robot, a piezoelectric microgripper, a tool changer and a tool magazine. These devices allow us to perform sequences of elementary micromanipulation tasks of objects of size between 20 and 500 μm. The choice of a suitable pair of tools (shape, initial gap between both tools, roughness) depends on the characteristics (shape, size and material) of the object to manipulate, adhesion problems (material and surface of contact) and the assembly task to perform.

The working principle of the tool changer is based on a thermal glue that permits us to fix the pair of tools either on the tip of the actuator or on the magazine. Hundreds of tool exchanges can be performed automatically with a maximum position error between two consecutive tool exchanges of 3.2 μm, 2.3 μm and 2.8 μm on the X, Y and Z axes respectively. Thermal and pressure tests have been performed proving the possibility of using the tool changer not only in the air but also in vacuum environments. The tool changer brings flexibility and compactness to the micromanipulation cells: the volume occupied by the magazine ($25 \times 20 \times 9 = 4160$ mm^3) and one gripper ($32 \times 13 \times 10 = 4500$ mm^3) is comparable.

The tool changer was designed to be used with a microgripper but, based on its working principle, this tool changer can be adapted to other kinds of devices. In the same way, the microgripper can be fixed on nearly any kind of micromanipulator depending on the application wished for.

To manipulate objects with typical dimensions smaller than 50 μm, smaller tools than the current ones have to be used. With this aim, we are developing silicium microtools. It is also possible to use different kinds of tools such as an AFM cantilever. Due to recent progress in the miniaturization of Peltier devices, it will also be possible to use them instead of resistances. Finally our main current works concern the integration of force feedback, vision capabilities and a compliant support.

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