A MICROMANIPULATION SETUP FOR COMPARATIVE TESTS OF MICROGRIPPERS

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Topic: Microgrippers
Keywords: micromanipulation, microgripper, manipulation setup, repeatability measurement

Abstract

A micromanipulation setup allowing comparative tests of manipulation micro tools has been developed. Repeatability measurements of positioning as well as optimization of manipulation conditions can be run with parts of typically 5 to 50µm over a large set of parameters including environment conditions, substrate and tip specifications, and different strategies (robot trajectories at picking and releasing time). The workstation consists of a high precise parallel robot, the Delta^3, to position the gripper, linear stages to place the parts in the field of view and two microscopes for the visual feedback and position measurement. The setup is placed in a chamber for controlling relative humidity and temperature. An interface was developed to integrate every kind of tool on the robot. Automated operations and measurement have been carried out based on localization and tracking of micro objects and gripper. Integration of micro tools was successfully accomplished and comparative tests were executed with micro tweezers. Sub micrometer position repeatability was achieved with a success rate of pick and pick operations of 95%.

I. Introduction

Many micro and nano technologies require systems capable of complex manipulation of single micrometer sized objects with a nanometer precision. In order to become useful on an industrial point of view, these tools have not only to be adapted for micro components but also to be efficient and to allow a high repeatability in the positioning of a part. It could be very useful to compare different gripper principles and pick & place parameters in order to build the most robust and reliable manipulation tool for a given application.

At micro scale, pick and place operations have to deal with the domination of the adhesive forces at every contact areas on the gravity effect. A wide range of technologies and principles has been proposed to handle micro objects. Beside micro tweezers that were widely proposed around the world [1, 2], other principles as vacuum effect [3] or electrostatic force [4] for example were used to manipulate parts using a bigger effect than the adhesion. Arai [5] and Vögeli [6] describe clues to decrease the adhesion by some local modifications of the contact areas in order to facilitate the manipulation. On the other side we find systems that use this adhesion effect to pick the parts [7, 8]. Finally non-contact manipulations were developed using an ultrasonic wave principle [9] or by laser trapping [10]. Principles have been also combined to improve pick or/and place operations.

The control of the manipulation process is an important point to guarantee the quality of the operations. Tele-operation was improved by the integration of a force feed-back system that gives to the user a better understanding of the forces acting at this scale [11]. Concerning automated manipulation an important effort is necessary for the precise localization of the micro components and the gripper. Detection and localization based on CAD model for instance have been investigated as well as measurement of the grasping force based on the image of the end-effectors deflection [12].

Since micro components are all different by their size, shape and functions, grippers are nearly dedicated to a certain application. The possibility to use different grippers or at least end-effectors opens the door to the manipulation of many different micro objects. A system allowing changing the tips of a gripper is proposed by Clévy [13] and an automatic load of a MEMS gripper was developed by Dechev [14].

This paper presents a micromanipulation setup to compare micro tools based on different principles to handle objects of 5 to 50µm. The goal is not only to check the ability of a gripper to pick and release a micro part, but also to measure the repeatability of positioning with which we are able to pick and place this same part. As the forces acting in the micro world depend clearly on the environmental conditions and the quality of the contact areas, these parameters will be correlated to the measurements and so need to be controlled on the workstation. Further than the comparative tests these different parameters of manipulation can be modified to optimize any sequences of manipulation and also to define the limits in which reliable operations can be accomplished.

The paper discusses first the specifications needed to carry out comparative tests of microgrippers (section 2). Section 3 and 4 describe the different elements of the setup (hardware) and the control and user interface structure (software). Section 5 discusses the automation of manipulation operations. Comparative tests were carried out on tweezers-based grippers. Section 6 presents experimental results. Section 7 concludes this paper and presents the future work.

II. **Micromanipulation Setup: specifications**

The purpose of the setup is to provide the capability of making comparative tests between many kinds of manipulation tools. This comparison is based on reliability and positioning repeatability measurements among a panel of controlled parameters which include the environment conditions, the specifications of the materials at the contacts areas and the strategies used at the robot level.

As well known, the manipulation of micro parts is strongly related to the adhesive forces that act at each contact area between the end-effectors tip, the micro part and the substrate. Under the name of adhesive forces we find the electrostatic force, the surface tension and Van der Waals forces [15]. These forces make the release of such parts insensitive to the gravity. They are mainly dependant of the material and size of the parts in contact and of the quality of the surfaces, but can be influenced also by the environment in which the manipulation takes place.

Considering the two final situations where the micro object is either on the gripper tip or laid on the substrate, the progress of a micromanipulation sequence depends on the equilibrium of the forces acting at both interfaces “gripper tip – micro object” and “substrate – micro object” plus an external force (functional force of gripping). For this reason it can be interesting to make these tests with different kinds of material for the substrate, for the micro objects and if possible for the tip of the gripper. The quality of these contact areas can also be modified by playing with their roughness for example or by deposing any kind of coating. Under the denomination of environmental conditions relative humidity and temperature have a strong influence on the adhesive forces and thus on the reliability of pick and place operations. Other parameters of interest are more linked to the strategy used during the manipulation sequence as the trajectory, the dynamic and also to the shape of both the tip and the receiver area.

Finally the micromanipulation setup has to fulfil the following requirements:

- To interface and use different kinds of gripper: these tools can vary according to their gripping principle, their shape and bulk, their orientation comparing to the substrate, their actuation principle and the energy to supply. A standard mechanical link with the manipulator has to be provided with a special emphasis for the power supply (electrical connection as well as pneumatic for instance).
- To allow proceeding to position repeatability measurements based on a vision system: this specification requires a system with high resolution and precision of measure.
- To have a high level of automation in order to decrease the effect of the user on the operations and mainly to ensure repeatable operations.
- To allow different conditions of test with a good stability and control in term of movement and trajectory, environmental conditions, material and surface specifications at substrate and tips place as well as the manipulation of different micro components.

III. **System description: Hardware**

To fulfil the above requirements the setup needs high precision manipulators and vision system that are presented here as well as the standard tool interface. To monitor and control the environmental conditions the workspace is confined in surrounded walls (chamber). Figure 1 is a photograph of the micromanipulation station with a close view on the workspace.

A high precision robot developed in our laboratory, the Delta^3 robot, has been integrated to the setup to position the gripper. It is based on a parallel kinematics with three degrees of freedom and built with flexure hinges and non contact actuators and sensors allowing movements without friction. It presents a bandwidth of 400Hz and stroke of 4mm in all directions with a position repeatability of ±10nm [16]. This compact robot holds in a cube of 210mm side.

The chosen strategy is to have a fixed field of view for the microscope and to position the substrate and the gripper tips in and out of the focal plane depending on the manipulation sequence. The substrate is mounted on an x-y table in order to place easily the objects of interest in the working area of the robot and on a fine z-axis with a resolution of 100nm for a stroke of 300µm. The substrate can be easily changed and its only specification is to be transparent to allow the back view from the microscope.

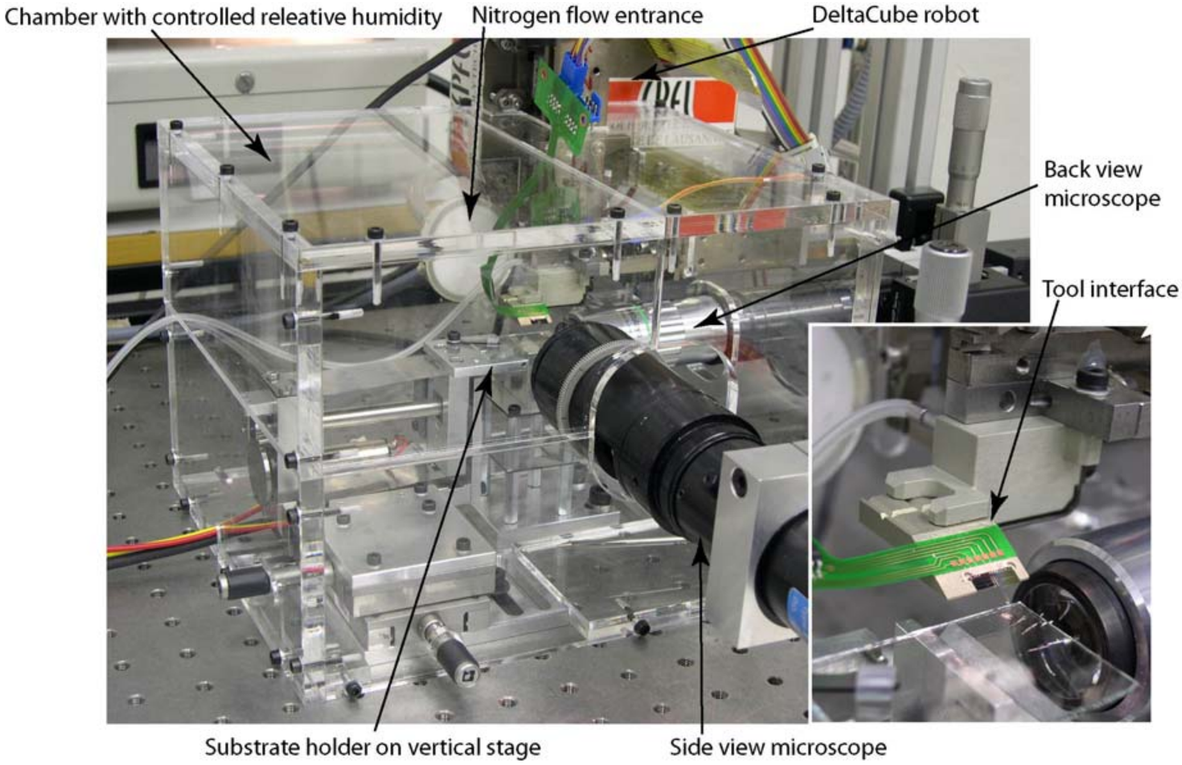

Figure 1: (left) overview of the micromanipulation setup; (right) close view of the workspace

A new interface is proposed allowing the integration of a very large range of gripper types with our robot (Figure 2). The connection with the Delta^3 is based on the contacts of three balls on three V-grooves and a pneumatic actuation. Closed by default, this interface presents a position repeatability of 300nm insuring the tool end-effectors to be always placed in the field of view. The design of the tool holder is free enough to allow the integration of different kinds of grippers with also the possibility to change the orientation of the end-effectors, but keep a "standard" configuration that allows to be grasped by the Delta^3. The power is supplied through a flexible PCB specially designed for each gripper or through a thin silicone tube for the air connection. An automated change of tools is in development. It will allow changing the gripper without to open the chamber to keep by this way the exact same conditions for all experiments.

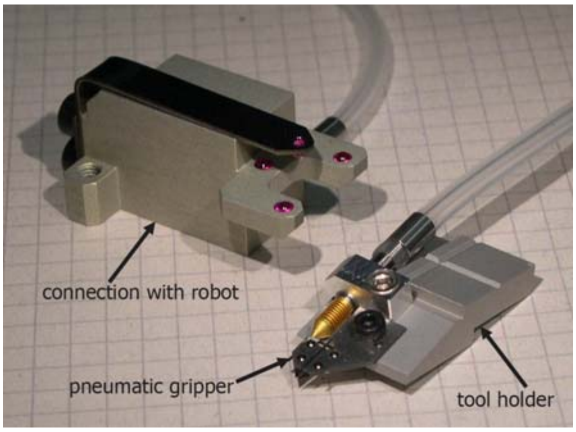

Figure 2: the standard tool holder with on the left side the connection piece with the Delta^3 and on the right side a pneumatic micro gripper on its holder.

The setup sits on the surface of a vibration-isolated table and is partly included in a chamber in which the relative humidity and the temperature are monitored. By injecting a controlled flow of nitrogen, the relative humidity can be set between 3% and 40%. The box surrounds only the working area and thus the controlled volume is small, allowing fast modification of the environment and a quick and easy access to every other system such as microscopes and x-y tables. The flow is injected through a sintered glass filter of 40mm in diameter with holes of 40 to 100µm to guarantee a homogenous and laminar flow in the workspace. Gas velocity was measured at 75mm of the filter corresponding to the manipulation position (Figure 3). An ion nuzzle is placed in serial with the gas flow. It has shown improving results of manipulation in case of highly charged elements implied on the operations. If experiments with a controlled and very stable temperature are necessary, the setup can be placed in the thermal insulated box used presently for the calibration of high precision robots [17]. A temperature stabilization of 0.01°C is then guaranteed.

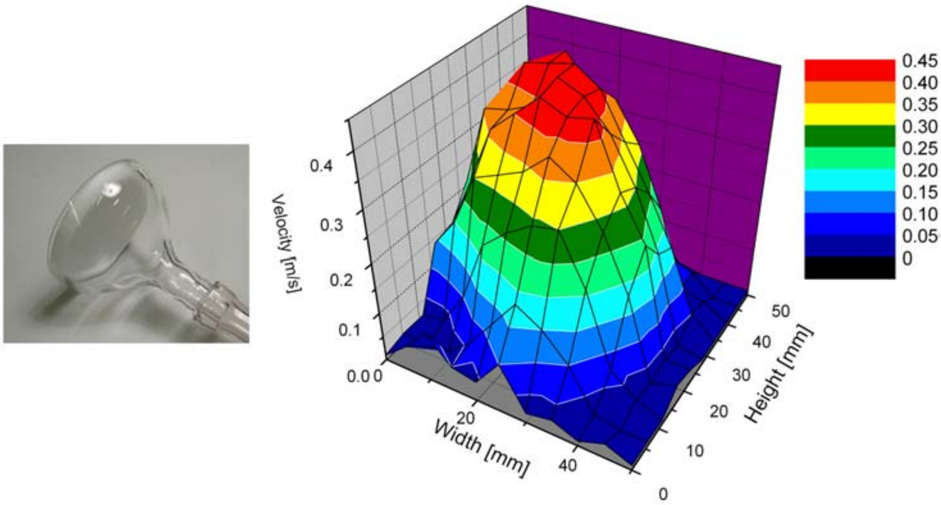

Figure 3: (left) sintered glass filter, diameter 40mm; (right) measure of the gas velocity at 75mm of the filter surface and with a pressure of 0.5bar.

The workspace supervision is given through a side view and an inverse view (or back view) based on two microscopes. Only the vision from the inverse microscope is effectively used to automatically localize both end-effectors tip and micro object and to proceed to each measurement. It needs thus to provide an image with a high quality and a high resolution. This microscope is built with commercially available components. It is based on a high resolution FireWire camera (1034x779 pixels, 1/3", and pixel size of 4.6 x 4.6 μm^2) and a microscope objective M Plan Apo (NA 0.42) placed on an Infinitube In-line Assembly. The optical system has a total magnification of 10x with a working distance of 20mm and a field of view of 470 x 350 μm^2. The side view makes easier for the user every step of the alignment procedure and allows him a fine supervision of the workspace. A USB camera mounted on a video zoom lens with magnification of 3x to 28x provides this additional view. The two microscopes are mounted on manual three stages allowing supervising the whole workspace of the robot.

The optical system of the inverse microscope has a coaxial illumination available. Combined with a direct diffuse lighting, these two systems give a good flexibility in the contrast choices. For example patterns, edges on the bottom surface of a gripper or active surface on a non transparent cantilever based gripper can be detected by using more intensity of the coaxial illumination whereas contours are easily detectable by the direct diffuse illumination.

IV. **System description: Software**

The control of the whole setup, robot included, is based on a biprocessor PC (Figure 4). One processor is dedicated to the robot controller, conceived by MoveIt Automation [18], with a real time layer running on Ardent RTX on Windows. It allows controlling the Delta^3 robot and the motorized z-axis. Analog inputs and outputs are then also used for gripper actuators and sensors. The application layer, implemented on C++, communicates with the controller via a dedicated library and processes the data from the vision system. The Graphic User Interface (GUI) has been developed using Microsoft Foundation Classes (MFC).

This choice of a unique PC was made because of a fast and easy communication link between the elements. By using separated processors for the controller and the application layer we ensure to have two separated loops without interference in the computational timing. This compact system is also compatible with the Microfactory concept [19] in order to confine and miniaturize not only the production and robotic operations, but also the command and the computerized parts.

From the GUI (Figure 5) the user receives all information about the robot status and position, the video streams and on demand the localization of gripper tip and part to manipulate. The robot position can be given in its own referential (direct reading of the sensor data) or relatively to the field of view of the microscope once the detection of the focal plane is done. Both views (side and back) are present on the GUI, but only the back view is used for the detection of the gripper tip and the parts as well as the localization of the focal plane. The image processing is based on the OpenCV library.

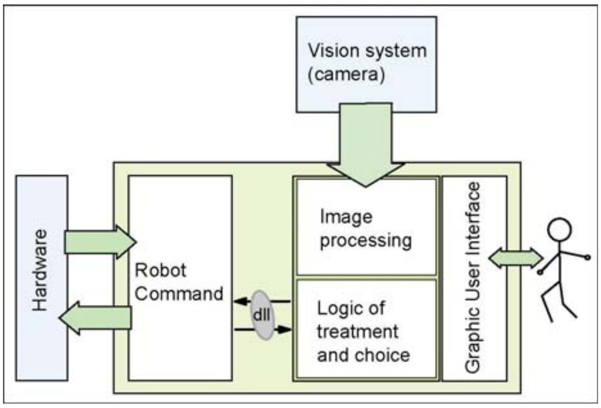

Figure 4: structure of the logic layer implemented on a biprocessor PC.

Two modes are available: manual and automated. The manual mode allows moving the robot based on absolute or relative displacements entered by the user. Tele manipulation can be done by this way based on the feed-back of the user through the camera images. The automated mode is used to make repeatable manipulation sequences. The alignments and measures will then be completed automatically during the whole sequence. This way allows us to compare different types of gripper, but also different strategies and sets of parameters for a same gripper with a minimal influence of the operator.

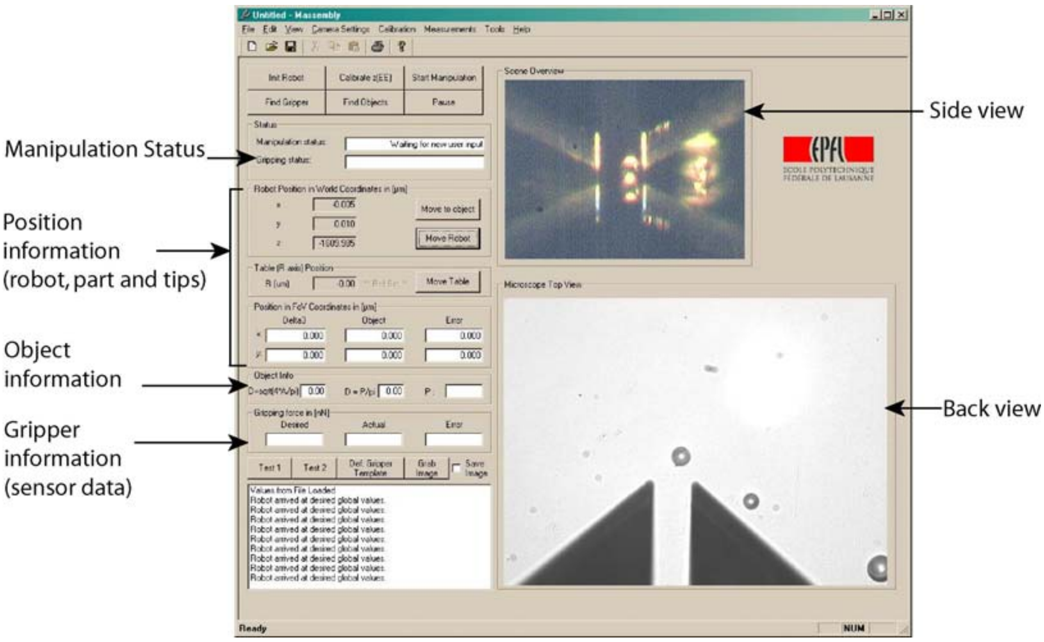

Figure 5: Graphic user interface with the two microscope views.

Some preparation tasks are necessary to set the automate manipulation as for example gripper specifications and offsets for the alignment procedure. These data can be created and measured from the interface itself and then saved for each tool. As several kinds of tool can be used, their description, if previously created, can also be loaded via a specific file that includes all information about their size, orientation, actuation, eventual sensor reading and all data for the image processing such as template and offsets. Different strategies (robot trajectories at picking and releasing time) can also be applied during the manipulation and are ready to be chosen and used in the GUI. Once gripper specifications and strategy are set, each manipulation starts by the choice of the part to manipulate and the target for the releasing. Switching from automate to manual mode can be done anytime without any lost of data, even during a manipulation sequence. The results as well as the historic of the commands and status are logged in specified files and pictures as well as videos can be saved from the GUI.

V. **Automated manipulation sequence**

The automation of manipulation sequences is based on the vision feed-back by measuring and tracking the position of the manipulated part and gripper tips during the whole process. The strategies concern mainly the alignment procedure as well as the way to release the part like the movement of the tips relatively to the micro object once the tweezers are open. Since they depend completely on the tested gripper principle they will not be described here.

The first step consists in the alignment of gripper tips and parts in the focal plane of the microscope. This auto focus is based on the maximisation of the image sharpness as presented by Buerkle [20] and does not need any knowledge about the shape of parts and tips. Considering the wide range of gripping principles that could be used, alignment on z-axis is subject to offset especially if cantilever based grippers (picking based adhesion for instance) are used.

The position repeatability measurement concerns the distance between the part and a specified target on the substrate. In an assembly operation the functional element of the component would be used for the alignment procedure. As this element depends of the part, we decided to define the position of a part as its centre of gravity. Since the micro objects to be manipulated can be of different shape and size, their localization method has so to be independent of this a priori knowledge. The implemented method is based on a segmentation applied to the microscope picture followed by a contour retrieving algorithm. This allows to detect all objects present on the picture and to ask the user to decide which one will be manipulated. The object data (area, position, bounding rectangle) are then saved in order to be used as an a priori knowledge for the tracking of the part during manipulation.

The implemented algorithm for the detection of the tool consists in the detection of a specific feature of the tip, defined in a template, by a correlation method followed by the addition of a specific offset to define the point necessary for the alignment procedure (Figure 6). It has to be kept in mind that the position repeatability measurement that is aimed hold on the part position and not on the tip position.

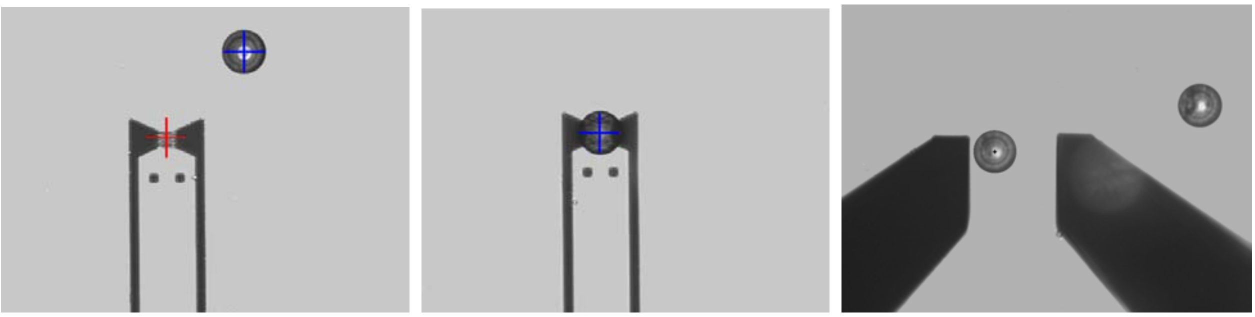

Figure 6: (left and middle) the two squares are here used as feature for the detection of the gripper and its positioning over the micro part; (right) the part is aligned along the tip border of the tweezers end-effectors.

To avoid a wrong measurement when manipulated part and gripper tips are touching each other, the gripper tip is first localized and its surface is then virtually shaded. The gripper tips are then considered as background. The detection of the part is applied on this final image.

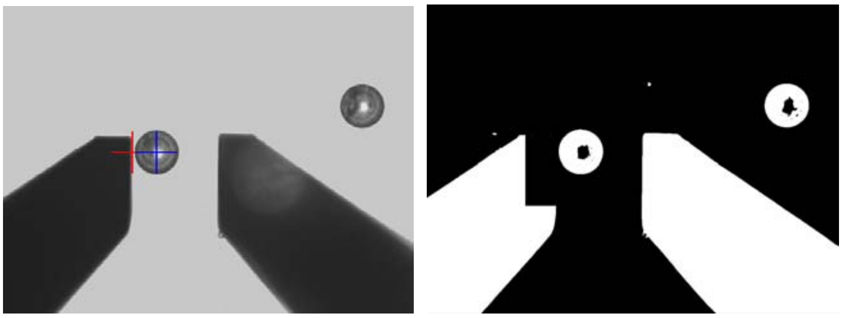

Figure 7: once the object is touching the tip (left), the tip is virtually shaded in the binary image allowing the complete detection of the part (right).

For the automated operations the image coordinate system needs to be related to the robot axes. This microscope calibration is made by measuring the position of a gripper tip or any feature fixed on the robot at different but known positions of the robot drawing a pattern along a grid. This method needs that the tip is in focus to be well detected. As no information is given about the displacement along the optical axis, the focal plane is assuming to be parallel to the robot XY plane.

The pixel to micrometer relation check, the validation of the method of localization and the determination of the accuracy of the measure has been made by using a precise pattern fabricated by IMT AG with our own specifications (Figure 8). The measure of the elements position on the image can be compared to the nominal values of the pattern since the maximum fabrication errors are smaller than the desired resolution for the measurement system (20nm). The performance of the detection of micro object is tested here. For absolute measurement, a shift of 300nm was observed during 10 minutes. This is due to relative movement of the elements constituting the measurement loop (Robot, optical system, z motorized axis). By using a fixed target on the substrate and measuring the position relatively to it, we got a stability of measure (σ) of ±50nm. The accuracy was evaluated to 0.5µm corresponding to an error smaller than 0.2% in average on this target-object distance.

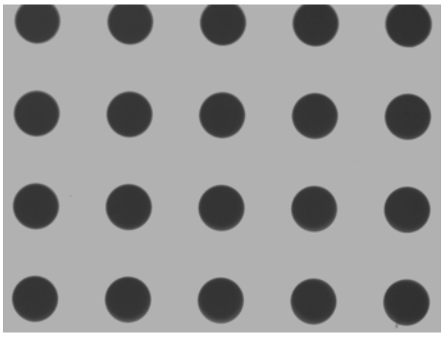

Figure 8: image through the microscope of the manufactured pattern used for the characterization of the measures, the disks have a diameter of 50µm.

VI. **Micromanipulations**

Currently micro tweezers have been tested on the manipulation setup. Other tools based on the adhesion principle, the use of an electric field, the vacuum effect or using the inertia effect of a part subject to a high acceleration for the release have been successfully integrated to the setup thanks to the tool holder. All of them were successfully interfaced with the Delta[3] (Figure 9). Comparative tests have been pursued with the micro tweezers according to different kinds of tips material and actuation for the gripper.

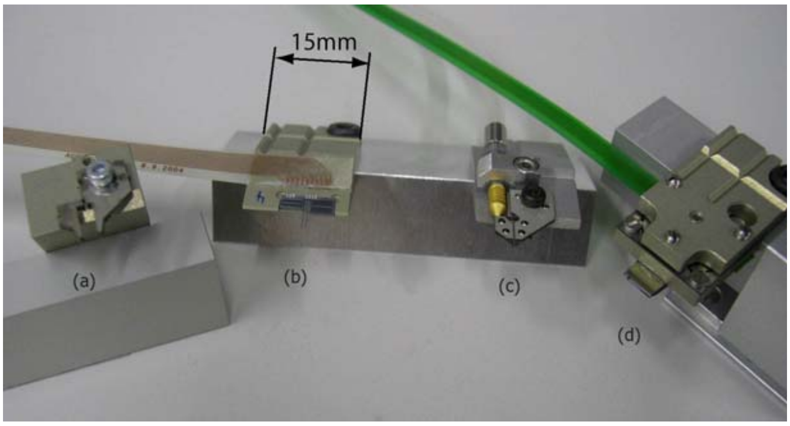

Figure 9: four different grippers mounted with different orientation: (a) tweezers with 12µm silicon tips (60° oriented compared with the horizontal), (b) MEMS gripper(30°), (c) pneumatic microgripper with 50µm steel EDM tips (30°), (d) electric field based gripper (horizontally oriented).

The first gripper is based on an electrostatic actuator that acts on a silicon finger tip of 50µm thickness. This MEMS gripper is monolithically designed and was conceived and realized in the Institute of Robotics and Intelligent Systems (IRIS – ETHZ). To change the conditions at the tip, we deposed a hydrophobic layer. The second gripper was developed to be low-cost with a short manufacturing time and very modular in term of the fingers specifications. It is based on stainless steel laser cut articulation actuated pneumatically. Stainless steel tips with thickness of 50µm as well as silicon tips with 12µm thickness were used.

Polystyrene balls of 50µm in diameter were manipulated in ambient conditions on glass substrates. Each test was run over about 60 trials. The comparison was made according to two measurements: the positioning repeatability at the release and the success rate of the manipulation. An operation is count as successful if the part was correctly released with a position error below 30µm. A success rate of 95% was achieved by using a MEMS gripper with a hydrophobic coating on the tips for a positioning repeatability of ±920nm. Table 1 summarizes the different results.

The main problem observed with non monolithic tweezers is the lack of control of the finger tips alignment. This error is induced during the assembly of the fingers or caused by internal stress. Consequences are some difficulties or even impossibilities to handle micro parts.

Actuator types	Tip specifications	Positioning repeatability	Success rate
Electrostatic	Silicon tips	0.74 µm	88 %
	Silicon tips, hydrophobic coating	0.92 µm	95 %
Pneumatic	Silicon tips	2.38 µm	91 %
	Stainless steel, hydrophobic coating	3.04 µm	74 %

Table 1: summarized results obtained on the micromanipulation setup for Ø50µm polystyrene balls.

The MEMS gripper gave quantitatively the best results with a positioning repeatability under the micrometer. Except the alignment consideration the electrostatic actuation presents also a higher resolution in the closure. The grasping force can be in that case better defined and above all weaker. As the adhesive effect is dependant of the contact area, a controlled and fine force allows limiting the local deformation and therefore the adhesive effect. These good results should not hide the fact that such MEMS grippers are cost effective comparing to an EDM/laser cut gripper. This low cost gripper could be sufficient for assembly tasks where for example mechanical references present on the substrate would ensure the positioning of the micro object.

From a detection point of view it has to be noted that as the stainless steel finger were cut by electro discharged machining (EDM), their edges are rougher than silicon fingers produced by an etching process. Even if a higher roughness should decrease the adhesive effect, in that case the detection of the part in between the two tips became less precise. The lack of control in the alignment of the two finger tips does also that the micro object was partly covered by them on the image and the localization was somehow biased. It is difficult to effectively quantify this error in the position measurement and this case of manipulation would anyway have no comparative results like the MEMS gripper. But it appears like a limitation in the precise detection of the part for the final alignment operation.

VII. **Conclusion**

We have presented a modular manipulation setup that makes possible to pursue comparative tests and positioning capacity measurement for handling micro tools. Thanks to a standard tool interface developed during the project, many kinds of gripper can be integrated and tested on the setup. Parameters as relative humidity, temperature, substrate and tip specifications as well as implemented alignment and release strategies can be correlated to the positioning results to study their effect on a manipulation sequence and to optimize a specific application or tool. Positioning repeatability measurement is possible since the setup presents detection and tracking system based on computer vision and a high automation level to minimize the effect of the user on the operations. Tele manipulation is available too for preliminary tests and trials.

Several tools were already integrated on the setup and experiments with micro tweezers were pursued. Position repeatability under the micrometer with a success rate of 95% was achieved in case of a MEMS gripper. Experimentations will be continued with modification of the environment conditions as well as with other tools.

These tests have shown that the setup is adapted to conduct comparative tests over different tools and conditions though vision based localization has to be improved to achieve a high accuracy in the measure. However the performances achieved allow simulating pick and place operations in similar conditions than micro assembly tasks.

VIII. **Acknowledgement**

This research is supported by the KTI/CTI Swiss Innovation Promotion Agency under the project “Manipulating Microscale objects with Nanoscale Precision” (Nr. 6643.1 & 6989.1). The authors would like to acknowledge Prof. B. Nelson and F. Beyeler from the Institute of Robotics and Intelligent Systems (IRIS – ETHZ) for the MEMS micro gripper conception and fabrication.

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