A complete manipulation platform for characterization of micro-components.

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ABSTRACT

This paper presents a complete manipulation platform for characterization of micro-components that is being developed in the scope of the European project GOLEM. Various tools such as electrical probes and force sensors have been designed and integrated on both high precision mobile micro-robots and fixed manipulators in order to interact with micro-objects. The platform enables the user to characterize parts with sizes ranging from sub-micrometer up to the millimeter. Forces ranging from 1 mN up to 120 mN can be measured as well as electrical resistivity of micro-components. As the characterization platform is aimed to be used by material scientists and biologists, the manipulation is "assisted" so that the user focuses on the application and not on the robotic systems. One of the key features is that the control software will automatically bring the end-effectors of the manipulators in the local (microscope) field of view.
The platform is composed of an XY stage mounted on an inverted optical microscope, of manipulators (fixed and mobile) and of various sensors (optical, force and electrical).

1. INTRODUCTION

The need for compact systems offering increasing functionalities (e.g cell phones integrating cameras, music player, GPS…) has driven the miniaturization of electronic and mechanical components. New tools are required to manipulate and assemble these components in order to create integrated systems.

Several companies offer characterization systems for micro-objects. These systems are often intended for a very specific characterization aimed for a very specific characterization and prohibitive cost for most of the research laboratories.

The characterization platform has been developed in the scope of the European project GOLEM, which is described below.

1.1 The GOLEM project.

The GOLEM project is supported by the Nanotechnology program (NMP) of the European Commission under the sixth framework program (FP6). It involves eleven partners both academic and industrial across Europe.
The goal of the GOLEM project is to use an approach based on bio-inspired events to assemble parts at the micro- /nano-scale. The objective is to mimic methods used by nature to interface organic and non-organic material and also to use molecules to uniquely define mating pairs between nano-objects to assemble. GOLEM's objective is to systematically investigate bio-inspired events as a "smart glue" to bond non-organic material.

1.2 Motivation for the development of the platform

EPFL's role in GOLEM is to provide a complete platform to fully characterize the assembly process of the micro-components on a substrate.

Various commercial systems are available for testing micro-components (like micro tensile testers) but these systems remains dedicated to specific tasks (mechanical testing, electrical probing …)

There is currently no device on the market offering a complete characterization (mechanical, optical and electrical) of micro-components. The objective is thus to provide the user with a platform integrating micro-manipulators and sensors to perform a wide range of characterization experiments.

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2. PLATFORM CONCEPT

2.1 Overview

The characterization platform combines both fixed manipulators and mobile micro-robots.

The sample to characterize is located on a XY stage (white plate on the Figure 1). Several mobile micro-robots are also located on the mobile plate of the XY stage and will thus move with the sample when the XY stage is actuated.
This special kinematics offers several advantages compared to a more conventional kinematics, especially for electrical probing of components.
For example, it is possible to place the tip of the mobile robot on a micro-sized object, and then to move the XY stage to go to another region of interest without losing the contact between the first robot and the first object. Another robot can then be placed on the newly observed object.

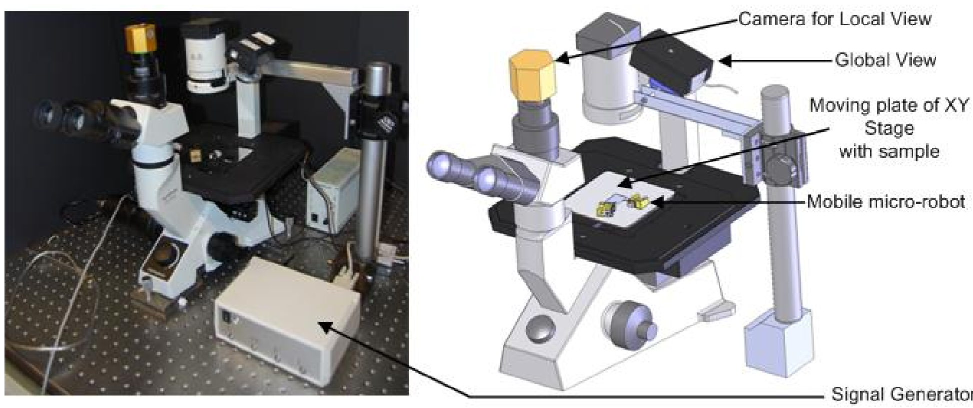

Figure 1 Overview of the platform

Conventionally, in most of the manipulation systems, the sample is placed on a moving stage, and the base of the manipulator is fixed on the base plate of the stage.

2.2 Characterization scenario

As a proof of concept, the samples to test are a set of SMD LEDs (Surface Mount Device – Light Emitting Diode). These LEDs are assembled on a transparent glass substrate so that they are visible through an inverted optical microscope.

Three types of characterizations of the bio-bonds will be performed:

- Characterization of the positioning accuracy of the part assembly, using both vision and touch-probing
- Mechanical characterization of the forces linking the micro-parts to the substrate.
- Electrical characterization, by measuring the electrical resistivity of the bio-bonds.

2.3 Components actuation

All the elements of the characterization platform are driven by piezo actuators working either in stick-slip or scanning mode.

The actuation signal for the stick slip mode is a saw tooth generated by a compact voltage amplifier designed within the LSRO group at the EPFL. This electronic is capable of generating a 400Vpp signal with a frequency up to 25 kHz and a high slew-rate (400 V/µsec). In addition to the scanning mode, the EPFL amplifier can provide a constant voltage to also drive the manipulators in scanning mode.

In order to reduce the number of signal generators required for the platform and to facilitate the implementation of the control software, all the manipulators (stages and mobile robots) are actuated using the same type of signals (saw tooth for stick-slip or constant voltage for scanning).

2.4 Vision systems

Two different vision systems are used on the platform

- A global view with a low magnification and a large field of view

The global view is used for the coarse positioning of the robots. This view will be used to navigate the robots autonomously to a position where the tool can be seen in the local view (close to the optical axis of the microscope).
The field of view of the global view is approximately 130x130 mm^2.

- A Local view with a high magnification and a small field of view.

This view will be used as a feedback when the user will manipulate the micro-parts.
In the platform the local field of view varies from 1500x1225 μm^2 (80x magnification) up to 300x225 μm^2 (400x, magnification).

3. MOBILE MICRO-ROBOTS

3.1 Structure and functioning principle of the robots

Thanks to their limited number of components and their simple Monolithic Push-pull actuators (MPA), the EPFL micro-robots are a robust and compact solution for tasks ranging from micro to nanomanipulation.
The MPA actuators used in the mobile micro-robots can be produced cost efficiently (even in small batches) in a standard environment using thick film lithography.

Monolithic Push-pull Actuators (MPA) have been developed at EPFL. Planar MPA is used as a locomotion platform for the mobile robots, offering three degrees of freedom in a compact and affordable module. These actuators are based on the push-pull principle to move the body of the robot over a substrate.

The planar actuator is composed of three sets of electrodes patterned on a piezo-plate. On one side of the piezo-plate, each set is subdivided in four smaller electrodes. On the other side, all the sets are linked and will be grounded. By applying a high voltage to specific electrodes of a set, the centre of the set can translate along two perpendicular axis. By combining the effects of the three sets, the robot can translate in X, Y and rotate in θz (see Figure 2).

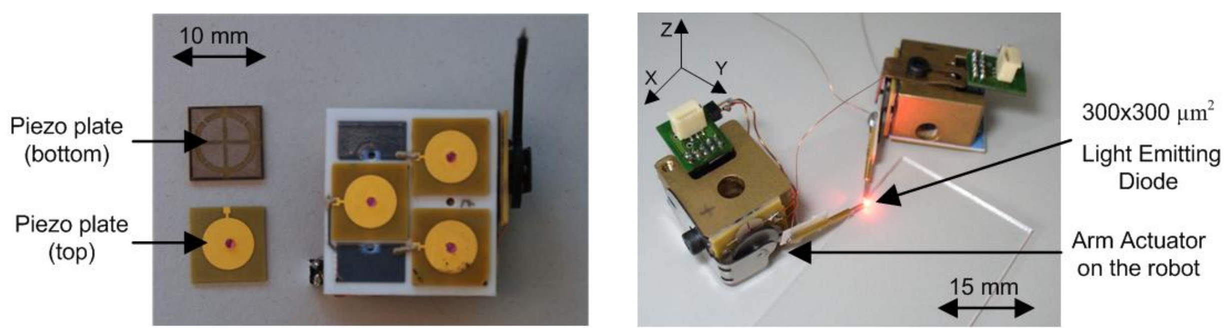

Figure 2 Left: Bottom view of a robot. Right: two robots used to light a diode

3.2 Robots actuation and wiring

As for the XY stage, the robots are actuated using the stick slip principle. Five high voltage signals and one ground are required to drive the robot. Completely autonomous micro-robots are a long term objective for the LSRO. Nevertheless

the priority for the GOLEM project is more focused towards reliability than autonomy. On-board electronics could cause various heating problems due to the high amount of power dissipated in the small volume of the robot.
With off-board electronics, the major problem to face is the wiring of the robots. As the size of the robot decreases, the wires, by their stiffness, will influence the motion of the robot.

3.3 Position and feedback control

In order to keep simple and reliable systems, the mobile micro-robots used in the GOLEM project do not have integrated position sensors.
Position feedback of the mobile robots is given by a set of two cameras see (section 2.4).
In the global view, two blobs located on the roof of the robot are tracked by a simple image recognition algorithm, giving the position of one or several robots in X, Y and θz.
Keeping only region of interest on the global view allows us to position the robot with an accuracy better than 100µm for both X and Y axis better than µm for X and Y, while keeping .
In term of performances, we can easily reach a 100 µm resolution at 50Hz by doing the processing of the image on a specific region.
This coarse positioning is sufficient to drive the robot in the local view (the size of the local view ranges from 1500x1200 µm² to 300x225 µm²).
Once the tip of the robot is visible in the local view, another tracking algorithm is used to improve the resolution of the positioning. We hope to reach a sub micro meter resolution, which is near the resolving power of optical microscope. This will lead to fast-automated high resolution manipulation under an optical microscope.
To reach this goal, feedback control is used. Currently; a simple proportional regulation enables the user to control and reach good precision and repeatability under the global view. More complex control feedback should ensure even better performance, as MPA and robot have a linear behavior at low actuation frequency (i.e. at low speed), as we can see on (figure 3).

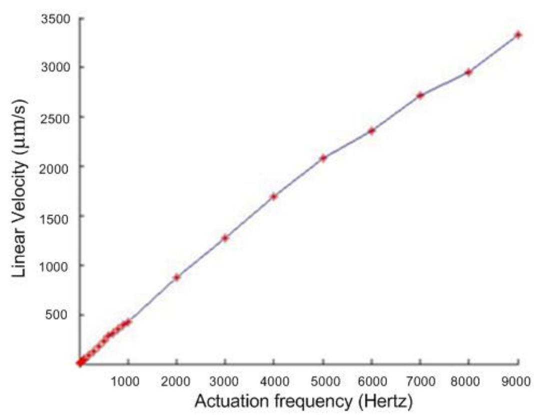

Figure 3 Linear Velocity of the robot in X, actuation with a constant amplitude of 400 V peak to peak

Another objective of the local view is to get the z position information (height) the tools currently used or the object observed. An algorithm driving the stepper motor of the focus has been developed. This algorithm already gives the z position of the observed object with a resolution better than 10 µm.

Further work is still carried out in order to reduce the processing time required to get the z position of the object.

3.4 Quick calibration procedure

As every sensor, the vision system used for the global view has to be calibrated in order to increase its precision.

The objective of the calibration system is to correct the geometrical aberrations due to the lens of the camera. A chessboard with perfectly known dimensions is used as a calibration pattern for the system.

An already existing C++ routine [3] has been implemented in the control software, to allow the user to easily re-calibrate the system in case the camera for global view has been moved. This routine gives us the parameters describing the distortion and the perspective deformation of the image.

Once these distortions and deformations of the image are known, a correction matrix can be used to get the “real” position of the observed objects.

4. XY STAGE

4.1 Structure and actuation

A low cost three-DOF XY stage has been designed for the GOLEM project.
This stage is composed of:

- A fixed plate mounted on the optical microscope
- A moving plate of 120x120mm^2 with a travelling range of 15 for both X and Y directions up to 5 mm/s
- three two-dof MPAs acting as the feet of the stage
- A three-dof position sensor (X, Y, θz) based on a CCD camera chip

The actuators used in the XY stage are based on the same technology than the one used for the robots. [2]

4.2 Position feed-back

A specific high precision 3 degrees of freedom position sensor has been developed for the XY stage [3].
The advantage of this sensor is its simple principle of operation. A fixed camera monitors the motion of a pattern on the moving plate. Thanks to a specific pattern of holes, the absolute position of the target can be obtained. This sensor has the advantage of sensing the motion in both X and Y directions (translations) but also θz (rotation) with a range going from 0° to 360°.

A miniature CMOS camera has been especially developed by Octax for better integration in the platform. This camera is used without a lens system as the moving plate and its pattern are both located at less than 50 µm away from the chip.
Care has been taken that despite the thin sensor chip (0.8mm) and the high packing density no component on the top side stands higher than the image sensor.
The camera is based on a color Omnivision SXGA chip, which can be operated at different resolutions up to 1280x1028 pixels.

4.3 Pattern on the target

The target for absolute position coding consists of two types of blobs with different size as shown in Figure 4.
One unit cell with a square shape has four grid blobs and one absolute marker. Different diameters of blobs permit to distinguish between grid blobs and absolute markers. Grid blobs can be found by calculating the area of blobs in the grabbed image. The distance between grid blobs along X direction is different from the distance along Y direction to distinguish the directions. The left-upper grid blob of a unit cell is considered as the origin of a local coordinate system. The change of the origin can give incremental position information. The x and y coordinates of the absolute marker with respect to the local coordinate system varies in certain increments. Absolute position coding is carried out from these coordinates information. For example, if x coordinate of the selected absolute marker increases by 50 µm in x direction offset increases by one.

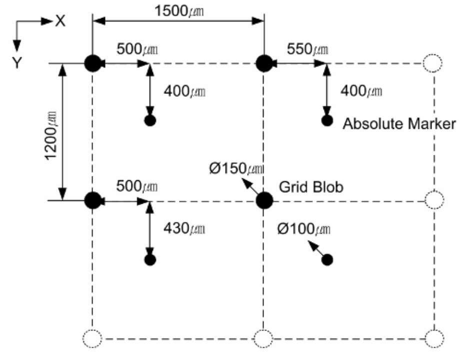

Figure 4 Pattern on the target for absolute position coding

4.4 Characterization of the proposed sensor

The sensor resolution can be characterized examining the variation of reading from sensor without moving the target. The resolution is given by 6σ, where σ is the standard deviation of the variation. Figure 5 shows the variation in X direction for approximately twenty minutes.

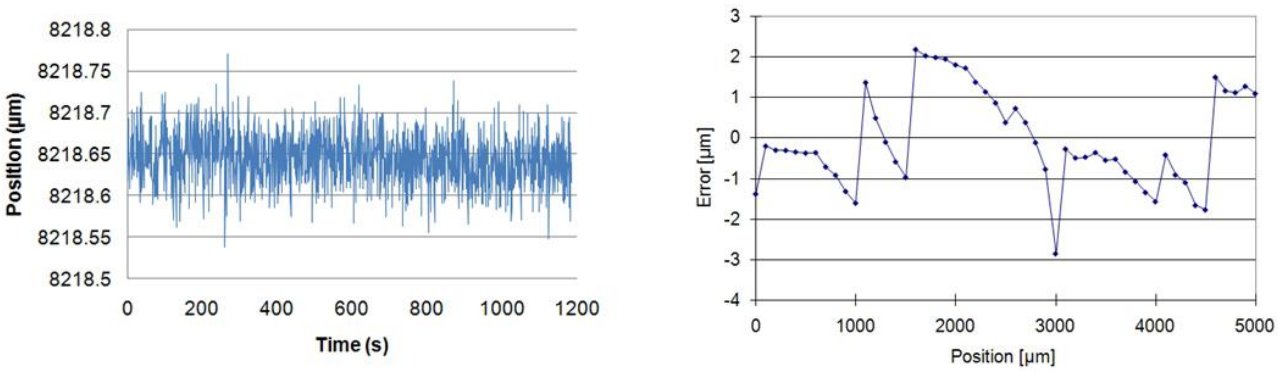

Figure 5 Left: The variation of reading from the sensor without moving the target Right: The accuracy test of sensor with 100μm steps using a laser interferometer

Before implementation of the sensor on the final platform, the accuracy of sensor was tested by comparing to a laser interferometer. The actual displacement of the target was measured by the interferometer. The target on a motorized linear stage moved with 100 μm increment steps over 5 mm travel range. When the selected units change, there appear peaks of the position difference between the sensor and the laser interferometer. This phenomenon is mainly due to the imperfection of the target fabricated by laser cutting method.

The repeatability of the sensor can be described by the variation of actual displacement while moving toward same position repeatedly. From an arbitrary point, the target was moved and returned to previous position with step sizes of 1 μm, 100 μm, and 1 mm for 20 times. The standard deviation of actual displacement of each case multiplying by 6 is then defined as repeatability.

Table 1 summarizes the specification of the sensor characterized by experiments and table 2 shows computing times for each procedure. Blob detection procedure consists of conversion of the acquired image to gray scale, image binarization by thresholding, and detection of the center coordinates of blobs.

Resolution	0.257 (μm)
Repeatability	0.236 (μm)
Accuracy	±3.459 (μm)
Processing time for one cycle	239.584 (4.2Hz)

Table 1 Measured characteristics of the sensor

4.5 Control of XY stage with the proposed sensor

One computer system is used for implementation of the proposed sensor and the other system is used for feedback control. The communication between computers is done through RS-232 serial ports. The measured position and angle information are sent to computer for feedback control in every routine.

4.6 Future work

The accuracy of the proposed sensor is not good enough compared to its resolution and repeatability. The distance between grid blobs directly affects the measurement result. The accuracy of the sensor can be improved with more precise hole pattern. The second thing to be done is to reduce the computing time by optimizing image processing or using a new algorithm. Reduction of computing time will make it possible to obtain faster sampling time.

5. TOUCH PROBING SYSTEM

5.1 Motivation for designing a touch probing system

In order to characterize the mechanical strength of the bio-bonds, a 3 dof (degrees of freedom) force sensor has been developed. The expected force is some dozens of mN.

The difficulty to find a commercial force sensor with the targeted range (1-120mN) and resolution (1 mN) has motivated the development of a custom designed sensor.

By using this force sensor as a touch probe, contacting a sample located on an XY stage, it is possible to perform metrology.

5.2 Sensing principle

When a force is applied at the end of the touch probe, it induces a deformation of a flexible membrane (see Figure 6 Force Sensor). A low cost optical sensor is used to detect this deflection with a range going from zero up to 500 µm.

The output voltage of the optical sensor is finally proportional to the force applied on the end-effector.

The deformation of the membrane is measured in three different points. For each point, a set of two sensors are used in differential mode in order to compensate mechanical and thermal drifting effects. The stiffness of the membrane is chosen according to the expected force range to measure.

The force sensor has been designed in a modular way, so that only the membrane has to be exchanged in order to measure forces over a different range (increasing or decreasing the stiffness of the membrane).

Preliminary measurements have shown a resolution of almost 1 µm for the optical sensor. The output voltage of the sensor ranges from -12V up to +12V. The estimated deflection of the membrane at full scale is 200 µm for both X and Y axis. Thus the estimated resolutions for X and Y is 0.6 mN.

Practically we are limited by the noise on the output electronic signal, which has been measured as 50mV (without filtering). The resolution of the sensor can be increased by making measurements using the diodes with a pulse current.

In this first prototype we are using an analog output. We process the data with a computer in order to decouple the measure. For a future work, it is planned to use a microcontroller to make measurement by pulse with higher current. The pulses have two advantages; the first one is that the LED produces less heat.

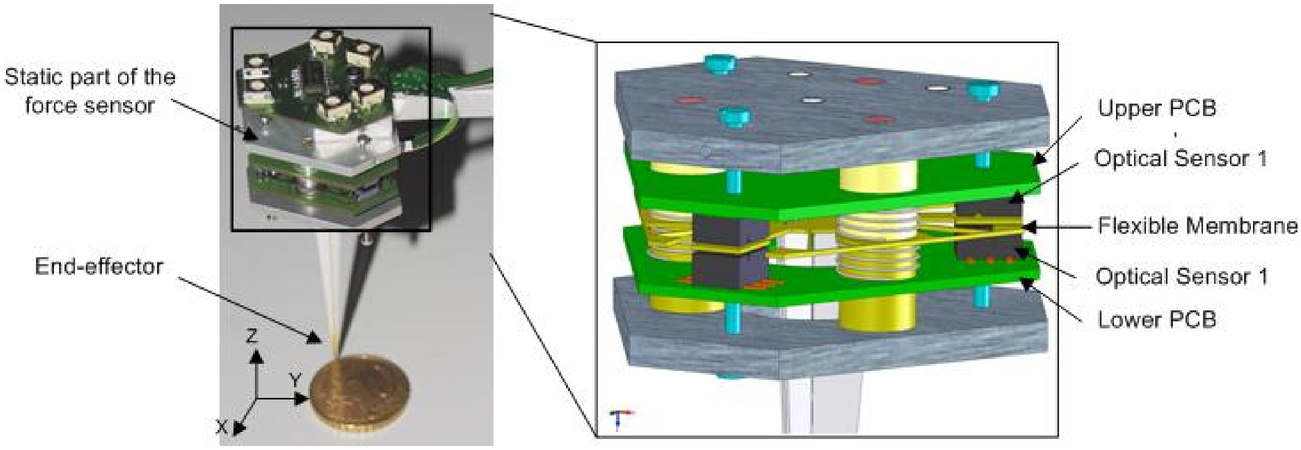

Figure 6 Force Sensor

The whole sensor has a compact size, with an overall dimension of 70x32x27 mm^3.
The probe is made with steel of 200 µm of diameter in order to contact objects of approximately 300 µm.

	Range (mN)	Resolution (mN)	Sensitivity (mV/mN)
X axis	120	0.6	100
Y axis	120	0.6	100
Z axis	1000	5	8

Table 2 Characteristics of the force sensor

5.3 Integration of the Force sensor on the touch probing system

The 3DoF force sensor is mounted on a 2 dof manipulator which is fixed on the base plate of the XY stage (see Figure 7). The manipulator is composed of two similar 1DoF linear axis. The aim of this manipulator is to bring the force sensor in contact with the micro-object to measure. Like the other manipulators presented in this paper, the linear axis are driven with piezo actuators working with the stick-slip principle.

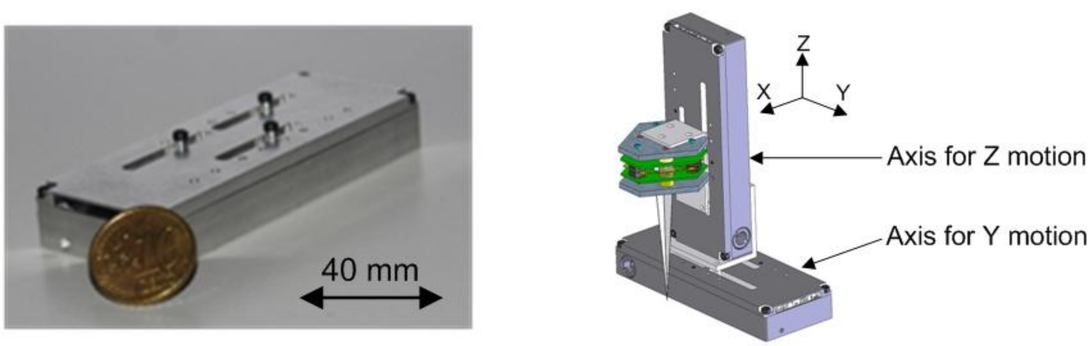

Figure 7 Left: Linear axis Right Force Sensor assembled on two linear axes

6. OVERALL PLATFORM CONTROL

The whole platform has been created to be easily used in any manipulation situation. It is developed to provide a maximum of automated task, without loosing the possibility to take back at any moment the control. Using well-design functionality, we can rapidly map the sample, mark position and get back to those positions automatically to do some test.

6.1 Architecture of the control

The control is organized in two levels: the first one is described in 6.2, the Graphical User Interface and the second one is composed of different dynamic libraries (dll). In addition some drivers are used to interact with the various peripherals, like the joystick, the gamepad, the motor of the autofocus, and the cameras.

These dlls are used in this way: one for the electronic driving, on the robot command, one for the vision system (two cameras) and one for regulation of the robot.

The vision system works in an independent thread in order to run the program in a non-blocking way. This system returns to the main thread the information concerning the robots positions (x, y and θz). This information passes then through the robot model process which regulates the closed-loop of the robot positioning system. The speed is computed from the position error and then converted into frequencies which are sent to the actuation channels, respecting to the speed-frequency ratio. The feedback closed-loop is performed with a proportional regulator. The Kp parameters have been optimized using an experiment plan, finding the minimal time to reach a simple displacement position.

The whole regulation process can reach a frequency of 50 Hz, including the grabbing of the camera image, the robot list management and the regulation itself.

6.2 Graphical User Interface.

The GUI is designed to offer various functionalities in a user-friendly way, allowing complex and high precision tasks in an efficient way. Each function is integrated as an autonomous module of the whole platform. These three modules are:

1. Auto-focus module: allowing to automatically focusing on an object in the local view, it can give the height of the focused object.
2. Feedback control of robots and XY stage allowing to store interesting positions in the whole sample
3. Auto-positioning of a manipulator in the center of the local view.

CONCLUSION

6.3 Other potential applications

In addition to the task performed for GOLEM, the characterization platform can also be used for many other applications:

- Micro-biology: cell injection, micro-surgery…
- Electrical probing of micro-electronic devices
- Metrology: 3D touch probing of micro objects
- Force characterization of a wide range of micro objects such as fibers, soldered components...

6.4 Future work

All the manipulators have been developed, fabricated and successfully tested. Now, all the components have to be integrated in the final setup and the first characterization of assembled meso-scale parts will start.

An environmental chamber that is an important part of the platform will be integrated within the next months. It will permit to control the environmental parameters (temperature, pressure and in humidity) by closing the set-up by a chamber during the experiments. This part of the platform is currently developed by Delong, an industrial partner of the project [5].

One other point that will be important in the last year period will be the integration of an on-board electronic amplifier for mobile micro-robot. That will be the first step of a long term development which aims to obtain a total autonomous mobile micro-robot. This electronic is also developed by an industrial partner, from Germany, that is specialized in hybrid electronic devices development, Quintenz [6].

ACKNOWLEDGEMENTS

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