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MICRO MANIPULATION AND ASSEMBLY

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Abstract

The paper describes the research activity jointly carried out by the Universities of Brescia, Bergamo, Ancona and the Institute of Industrial Technologies and Automation of the Italian National Research Council, focusing on the main issues concerning the manipulation and assembly of extremely small components. Beside analyzing theoretical and practical aspects, the project, funded by the Italian Ministry for Education, Universities and Research, aims at the realization of an automated test bed for the assembly of micro pieces whose typical dimension belongs to the submillimeter scale range. The perspective is to contribute to the realization of general automatic production systems at the moment absent for objects of these dimensions.

Keywords: Micro manipulation, micro assembly

1. Introduction

Nowadays in the microsystems production, i.e. MEMS (Micro Electro Mechanical Systems) or MOEMS (Micro Opto Electro Mechanical Systems), the assembly task impacts more than 60% on the final cost of the product. High skilled labour, able to perform manual assembly, is necessary, and in most of the cases this procedure is difficult, tedious, time consuming and very expensive.

For this reason innovative computer-based automated assembly methods need to be developed in order to increase efficiency, reliability, and reduce costs. This necessity leads to new possibilities for the fabrication of innovative devices, but it also implies many challenges that the differences between micro- and meso-scale assemblies carry as result of operating with micrometric part sizes and tolerances.

Among these challenges it is worth to mention:

- the high precision requirements that have traditionally been obtained at the expense of system cost and complexity;
- the identification of the right gripper for the micro-scale assembly, since the interaction forces between grippers and parts may affect the correct part release, and the absolute position of parts and tools is much more difficult to measure;
- the downscaling of microassembly solutions that employ conventional assembly concepts; the effectiveness diminishes as part dimensions shrink;
- the development of extensive calibration procedures.

Despite all these problems, in the last decade, miniaturization has spread out in all the consumer oriented products (e.g. mobile phones) with the integration of more and more functionalities in an increasing smaller space. Together with MEMS and MOEMS made of silicon, other microproducts,

called hybrid, have been proposed. They present a 3D geometry and are made of a lot of components, each of whom is fabricated with the most appropriate material and process for its function.
These microproducts hugely increase the number of fast-paced industrial sectors that they can pervade: from the IT to the telecommunication, from the industrial automation to the transportation, aeronautics, aerospace and automotive, up to sectors of greater social impact like the medical and biomedical ones.
In order to handle the increasing request of these components, in the 90ies, the Mechanical Engineering Laboratory (MEL) of the AIST in Japan, introduced for the first time the concept of "Microfactory", referring to a miniaturized and reconfigurable system for the production of microproducts. After twenty years this concept is now widely recognized in the international and European scientific community, but not yet enough wide spread.

2. Objective of the project

The purpose of the research activity is to contribute to the realization of general automatic systems for the production of microparts, since such systems are not available at the moment for objects of this size.
For this reason the project represents the right opportunity to tackle the above mentioned issues, developing and implementing:

- methodologies for the analysis, synthesis and design of meso/mini manipulators able to accurately and precisely position and orient in the space parts with overall dimensions of about 500 microns;
- methodologies and strategies for the microparts grasping, handling and correct release, taking into account the adhesive effects and the predominance of superficial forces over mass and inertia;
- methodologies and strategies for robot and workcell calibration;
- measuring methodologies and strategies, based on vision systems.

More in detail the project aims to develop: innovative microgrippers; innovative positioning and orienting systems with accuracy and repeatability of few microns and overall dimensions of few centimeters; monitoring systems for pieces recognition and devices calibration and supervision.
The success of the overall research activity will be proved by the assembly of a benchmark. It consists of a cube/pyramid showing holes with different shapes on its faces, through which compatible pieces are inserted by a micromanipulator. The cube is correctly oriented by an orientation platform.
The specifications of the objects that the workcell will assemble are precisely defined using criteria of representativeness of the various categories of micro parts. Different materials, dimensions, shapes, qualities of the surfaces and masses are considered.
The identification of the manufacturing tolerances takes into account the technological constraints of the micro-working processes available. As a consequence, the performance of each device is defined in terms of operative range, maximum dimensions, precision, hardware and software interface with the others devices.

While in the first part of the project each individual research unit focuses on the design and test of its own device (stand-alone), in the second phase all the devices are assembled into the same workcell and the above mentioned methodologies and strategies are implemented and validated in a final demonstrator, a test bed where the developed devices (manipulator, orienting platform, microgripper) are integrated and properly interfaced to a control and supervision system, and collaborate to automatically execute some representative micro-assembly tasks.
The test bed will show the feasibility of a low cost, fully automatized, "general purpose" assembly minicell. It will overcome the current limitations, mainly due to the

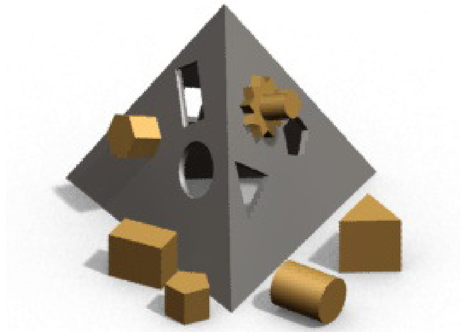


Figure 1: The demonstration assembly task

complexity of the manual assembly process and the related low productivity of a mass production approach, in the realization of hybrid 3D complex microproducts. In order to realize the above described cell, the existing techniques for the design, production, calibration and coordination of components are improved.

New methodologies and techniques are developed for the devices calibration, part detection and recognition, measurements, orientation and position detection, path planning, handling, grasping and releasing. The measure of the demonstrative workcell performances will allow a qualitative and quantitative evaluation of the results achieved in every single phase.

Hereinafter the test bed assembly task is described (Figure 2). A vision system identifies position and orientation of an object randomly positioned in a micro pallet which is available at a predefined area. Different pieces with different shapes and sizes will be selected from a predefined set.

A manipulator grasps the object and inserts it into a cube/pyramid whose correct orientation is assured by an orientation platform. A global number of 6 degrees of freedom guarantees the accomplishment of the task.

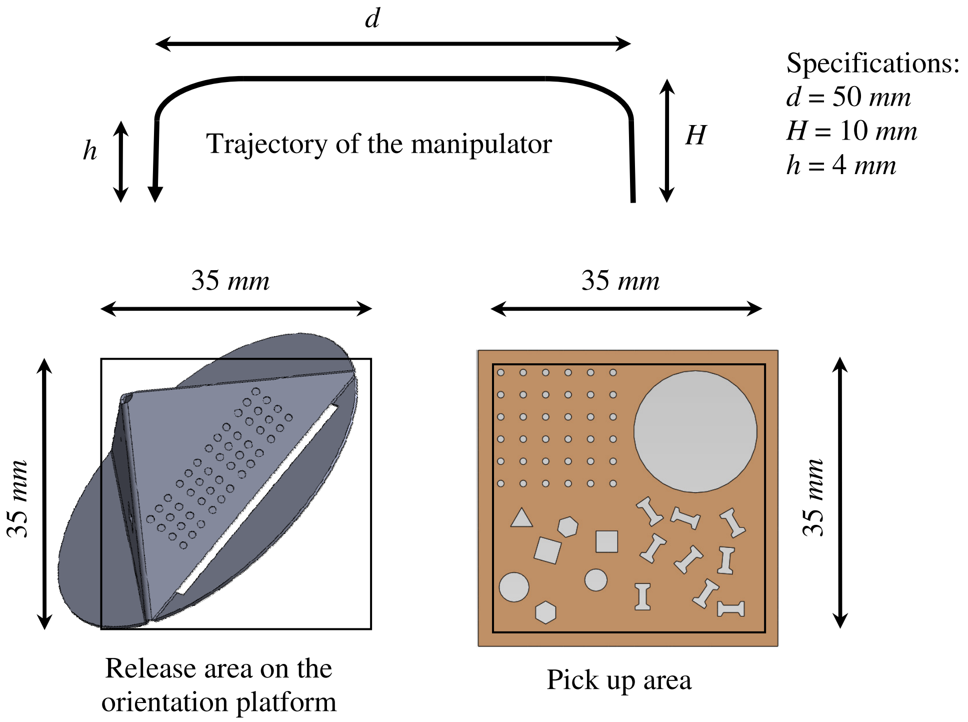


Figure 2: Sketch of the pick up and release working areas and trajectory of the manipulator

3. Positioning system: the manipulator

At the present stage of the research project, all the main specifications are defined and fixed. The basic design requirements for the micromanipulator can be summarized as follow:

- the miniaturized assembly robot should provide 4 DOFs and guarantee translational motion along three orthogonal axes (x, y and z) for the positioning of microparts in the Cartesian space and rotation α around the z axis for their orientation (Shoenflies motion);
- the shape of the manipulation workspace must contain a prismatic volume whose projection on the xy-plane is a rectangle 85x35 *mm*, and its extension along z direction is 20 *mm*;
- the manipulator theoretical repeatability on the xy-plane should be less than 10 μm, while its resolution should be around 1 μm.

Based on the required specifications, after analyzing several industrial and research microrobots [1], the kinematics structure of the micromanipulator was selected.

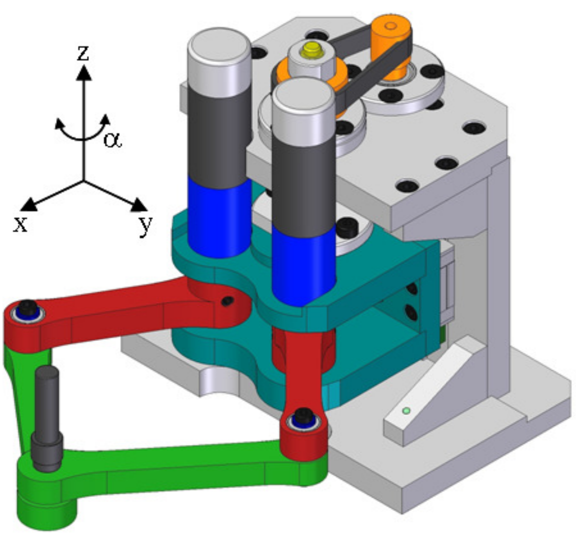


Figure 3: Virtual prototype of the 4-DOF micromanipulator

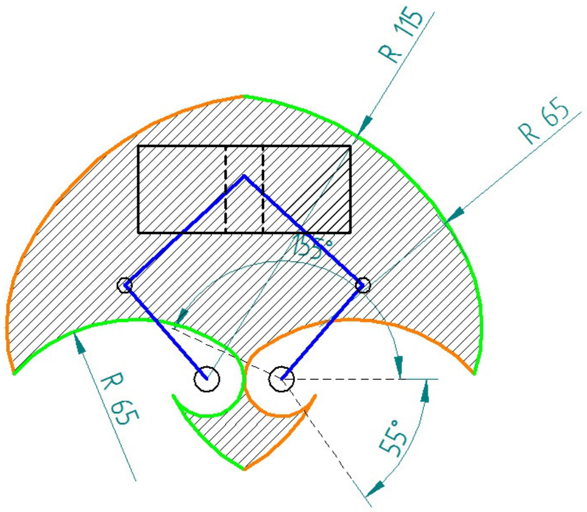


Figure 4: Reachable working area; the solid line rectangle represents the required workspace

The chosen kinematic architecture presents a hybrid structure. In particular the motion in the ***xy***-plane is obtained by a five linkage parallel kinematic mechanism (double SCARA), the motion along the z axis is realized moving the whole manipulator vertically, while the rotational axis is located on the moving arm.

A preliminary and "non-optimized" virtual prototype of the hybrid manipulator is depicted in Figure 3, while Figure 4 shows its reachable workspace (projection in the ***xy***-plane).

Presently, the research activity is mainly focused on defining the most suitable methods for the kinematics and dynamic synthesis of the selected manipulator and on the integration of the driving systems in the mechanical frame, with particular regards to the identification of the transmissions and couplers suitable for the required performances. To this end, several software tools for the synthesis and optimization of the micromanipulator have been realized. The simulation code allows to monitor several kinematic and dynamic performance indices. More in details, among others, it is possible to calculate some local and global dexterity indices such as the condition number κ of the jacobian matrix $\mathbf{J}$ of the system and a kinematic manipulability measure defined as the square root of the minimum eigenvalue of $\mathbf{JJ}^{\mathbf{T}}$. Moreover, assigning a reasonable mass distribution to the system, it is possible to preliminary compute the torque exerted to the joint and other synthetic indices such as a dynamic manipulability measure [3].

As an example, Figure 5 and Figure 6 show the condition number and the manipulability measure in the ***xy***-plane for the micromanipulator depicted in Figure 3.

Another useful measure to take into consideration in this design phase is the positioning sensitivity in the workspace. In particular the sensitivity of the structure (i.e. the uncertainty of the robot's pose caused by uncertainty in the position of the joints) is computed at all points in the workspace and its mean value in the working area is considered. This information is crucial to select the suitable encoders in order to achieve the required resolution in the Cartesian space, and to preliminary estimate the influence of the transmission system inaccuracy (e.g. backlash, hysteresis, etc) on the manipulator pose. This aspect is very critical and plays a fundamental role in the theoretical repeatability of the manipulator. As an example, for the manipulator of Figure 3 a mean sensitivity of about 91 *mm/rad* is achieved, therefore in order to obtain the prescribed repeatability (less than 10 μm) a gearbox with a position accuracy better than 0.063° has to be selected. To the authors' knowledge, the only commercially available micro transmissions that offer this position accuracy are the micro Harmonic Drives developed by Micromotion [2].

The next step of the research activity will consist in carrying out the kinematics and dynamic synthesis of the micromanipulator and the identification of the most suitable driving system technology to attain the prescribed performances.

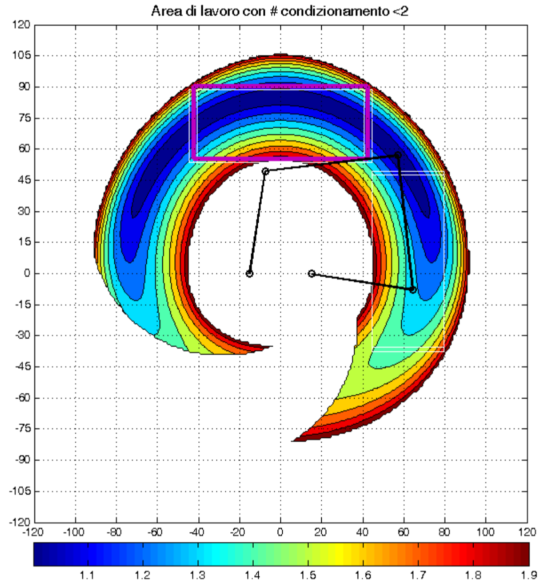


Figure 5: Workspace with condition number k<2. In the working area its mean value is less than 1.4

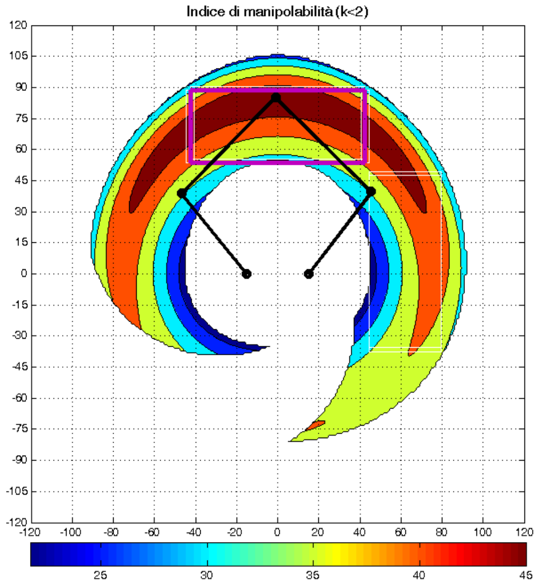


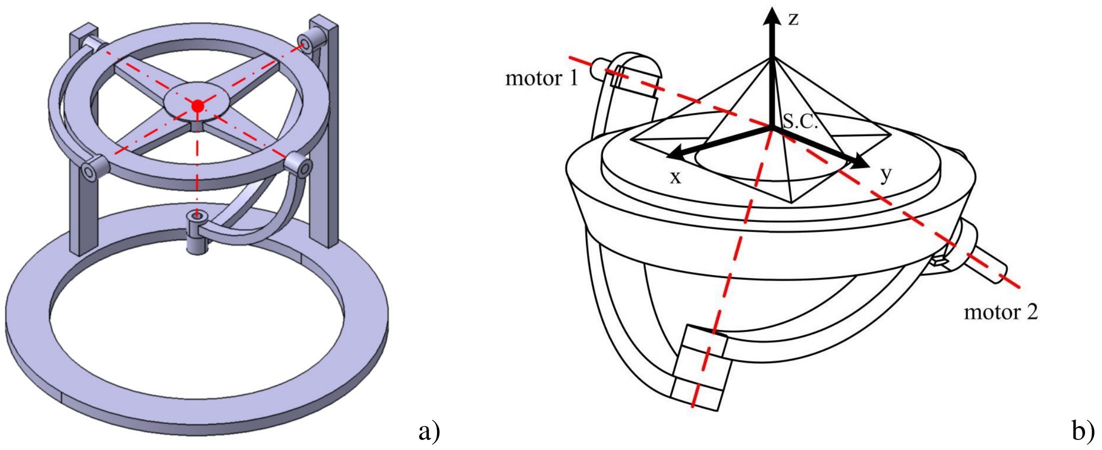
Figure 6: Manipulability measure, in the rectangular working area its mean value is about 42 *mm/rad*

4. Orienting system: orientation platform

Since during the assembly tasks a 2-DOF pointing device must guarantee the correct parallelism between pins and holes it has been conceived a mini orientation platform responding to the following requirements:

- 2 DOFs of rotation;
- a minimal workspace of ±45° about every axis lying on the horizontal plane;
- a payload of 30 *g* in dynamic conditions (a range of rotation of 90° in 1 *s*), increasing to 100 *g* in static conditions;
- overall size of a cube with a side of 150 *mm*;
- a resolution of about 10^{-2} degrees.

In order to confer high stiffness to the device, the design of the orientation platform was inspired to typical parallel kinematic structures, which give also a secondary advantage, being all motors fixed to ground.



a) b)

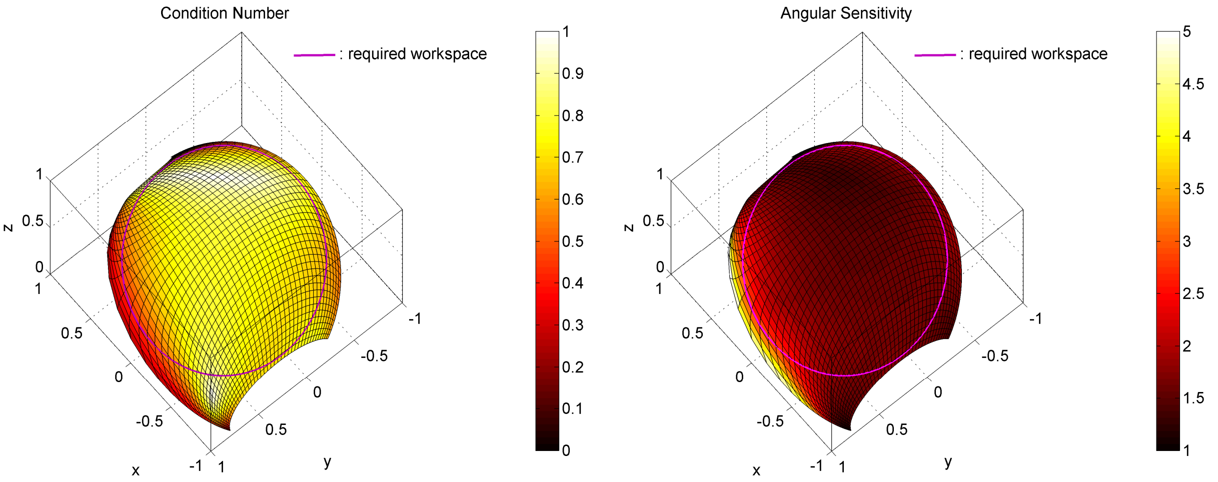
Figure 7: 2-DOF orientation platform:
a) Basic kinematic architecture; b) Optimized kinematic architecture.

The basic idea for the kinematic architecture is a spherical five-bar linkage actuated on the two rotation joints fixed to ground (Figure 7a) [4,5]; in such structure the centre of the spherical motion is at the intersection of all rotation joint axes. Starting from this idea an optimization process has been carried out pursuing two main objectives:

- to locate the spherical centre over the platform surface; indeed, if the spherical point is at the base of the swinging object, a rotation necessarily introduces a translation of the object face centroid, thus increasing the required workspace for the manipulator.
- to be able to orient upwards the faces of a pyramid with equilateral triangular base obtained cutting a cube with a side of 35 *mm*; this condition leads to a workspace of about ±54.7° around all axes lying on the horizontal plane.

A first architecture configuration resulting from the optimization process is shown in Figure 7b.

The study of the platform kinematics allowed to define the actual workspace that has been obtained with the maximum excursions of the motors avoiding interference between the members of the legs. Such workspace, as displayed by the surfaces of Figure 8, contains the locus of points imposed by the requirements. The analysis of the condition number, defined as the ratio between the minimum and the maximum eigenvalues of the kinematic Jacobian, ensures that no singularities are inside the workspace (Figure 8a). Figure 8b shows the angular sensitivity all over the workspace; such parameter indicates how a perturbation on rotations of motor shafts results in a global rotation of the platform. Inside the region of interest angular sensitivity is always lower than 3. Thus, assuming a motor shaft resolution of about $8.4 \cdot 10^{-3}$ degrees (resulting from a 512 counts encoder and a gearbox with a reduction of 84), the maximum end-effector resolution inside the required workspace is of about $2.5 \cdot 10^{-2}$ degrees.



a)

b)

Figure 8: a) Condition Number over the workspace; b) Angular sensitivity (ratio between encoder resolution and platform global rotation angle) over the workspace.

5. Grasping system: microgrippers

A still open research issue, in the design and manufacturing of micro-gripping devices, is the study of the size effects and of the growing influence of superficial forces (capillary, van der Waals, electrostatic, …) with respect to gravity and mass related forces [6]. Indeed, at the micro-scale, the predominance of superficial phenomena, together with effects negligible at the macro-scale, require design criteria and solutions different from those commonly used for the manipulation of macrocomponents. The release phase is often critical and failures, due to sticking effects caused by adhesion forces or electrostatic jump, are often reported. Therefore, methodologies and tools for the robust design of microgrippers will be developed, including modelling of superficial interaction forces between the gripper and the component, and between the component and the substrate. Appropriate gripping and releasing strategies will be investigated to guarantee the overall performances of the microgripper-robot system, in terms of: precision, accuracy and repeatability of the assembly process.

Different grasping and releasing principles have been and will be implemented to cope with the different shapes, materials and superficial qualities of the micro-samples.

In particular, commercial mechanical tweezers with different actuating systems (such as electrostatic actuation, hydraulic or pneumatic, piezoelectric control, SMA, and thermal actuation) will be evaluated and compared in order to select the most suitable and flexible [7, 8].

Moreover, the possibility to use grippers based on physical principles peculiar to the micro-scale will also be considered in order to control and exploit the adhesive forces. In this context, capillary and van der Waals based grippers will also be investigated.

Finally, vacuum grippers, based on the use of the force generated by the pressure difference between the gripper and the atmosphere, will be studied. Indeed, vacuum grippers are very common in the assembly of fragile macrocomponents and can be easily miniaturized. They can be very cheap as consist mainly of a micropipette connected to a vacuum pump.

For these reasons, the early research activity was devoted to the analysis, study and development of different types of vacuum grippers.

Thus far, the performance of two standard vacuum microgrippers (commercially available needles for dispensing) with respect to an innovative multi-lumen nozzle (designed by CNR-ITIA) has been critically analyzed. The benefits and limitations of these grippers, mainly in the releasing phase, have been highlighted and some solutions proposed [9].

In the same way as for the vacuum grippers, all the prototypes of microgrippers will be preliminarily tested on a commercial precision micromanipulator (Melfa RP-1AH by Mitsubishi) and then integrated with the positioning and orientating units in the final project demonstration set-up.

6. Vision system and calibration

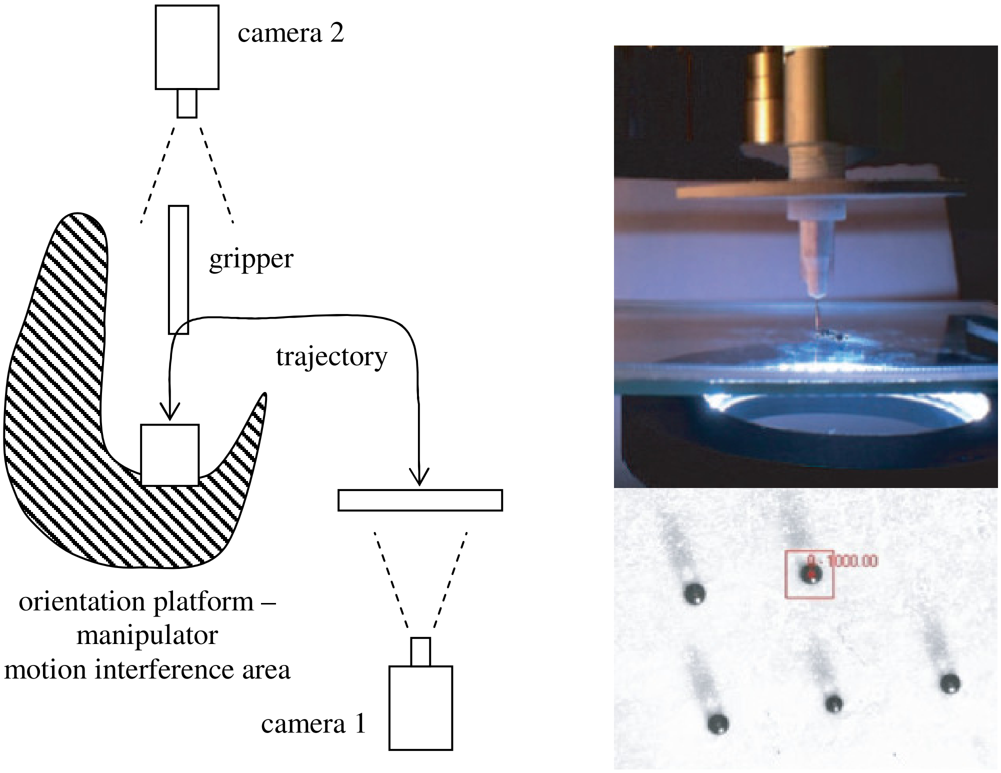
In order to develop a flexible workcell for micromanipulation and assembly, the use of vision systems can be greatly beneficial. Indeed, the design of a suitable vision system allows to recognize the different components and measure the position/orientation of the objects in the working space with the appropriate accuracy. In this way, the inspection for quality control and look-and-move or visual servoing robot control strategies can be performed.

For all these applications it is generally impossible to find a unique vision system setup, especially for micro-assembly applications. This problem mainly derives from the objects properties (shape, size, materials, colour, etc.) and environment properties (lightning, field of view, shape and size, etc.). For this reason, a lot of different applications and solutions are proposed in literature, such as 2D or 3D vision systems, fixed cameras or cameras carried by the manipulator end-effector, single or multi-camera vision systems.

Thus, the best vision system for the final workcell will be designed, taking into account the choice of the cameras, the camera lenses and the frame grabber. The robot workspace, the workcell size and the camera size, as well as the resolution of the measurements to be performed will also be taken into account. Moreover, a suitable lightning system will be chosen to cope with the critical aspects of image acquisition such as the type of lightning source and positioning, object reflection and colour of the parts.

Since in a workcell a robot and a vision system have to cooperate within the same working area, a robot calibration, a camera calibration and a robot-camera georeferencing (also called registration) are fundamental. Standard calibration methods result in a very onerous process at the micro-scale, thus non-conventional calibration strategies have to be developed and implemented in a preliminary workcell.

In this context, an experimental setup has been adopted to test different 2D vision systems layouts (Figure 9a).



a) b)

Figure 9: a) Layout of the vision system setup; b) Example of localization and manipulation

In this workcell prototype, different planar zones monitored by vision systems with different fields of view and spatial resolutions and equipped with different lightning systems were considered to ease the future choice of the most suitable solution for the final test bed. This prototype has been used as experimental setup for the study and implementation of 2D calibration strategies able to meet the tight requirements of the micro-scale. A novel calibration strategy based on the automatic construction of a virtual grid has been conceived [10]. It allows to simultaneously calibrate the camera and georeference the camera with respect to the robot without using external tools (as a calibration pattern and a calibration pin).

To build vision systems able to recognize the microcomponents to be manipulated and measure their position and orientation, a set of image processing and machine vision algorithms are being implemented, including geometric and pattern matching and blob analysis (Figure 9b).

7. Workcell layout: integration of the stand-alone devices into the final demonstrator

After validating each stand-alone system, verifying the possibility to execute the requested task and measuring significant performance indices in accordance with the UNI EN ISO 9283 standard, the different devices will be integrated into a workcell that will practically perform the desired task by manipulating and assembling 3D micro-objects.

Pursuing this goal all the involved research units will work to allow the integration of calibration procedures and to assure the presence of hardware and software interfaces between the different components.

All the devices will be programmed to execute the demonstrative task and tests to check the proper tasks execution will be performed together with measurements to supervise the performances of the whole workcell (object recognition, pose accuracy and repeatability, execution speed, time cycle, etc.).

In order to coordinate the movements of every mechanism, all the devices inside the workcell will be equipped with independent controllers (PC, PLC …) that will send alphanumeric strings to each other and to a “General controller” via Ethernet buses.

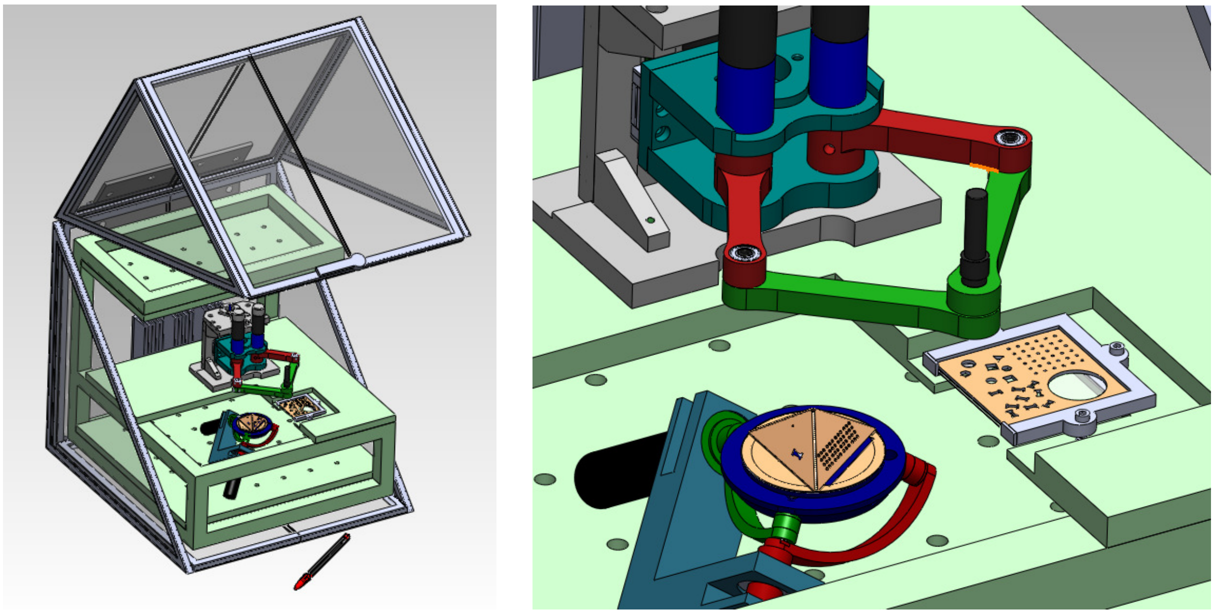

a) b)

Figure 10: a) Assembly of the micro-manipulation workcell; b) Detail of the working area.

A communication system based on the exchange of simple information and orders will be developed and point-to-point or trajectory movements that can be individually handled by the manipulator and/or the orientation platform will be considered.

Moreover, different solutions to avoid the side effects of uncontrolled variations in temperature and humidity are being studied, since these effects can generate undesired displacements of the parts and stiction, thus compromising the handling and assembling tasks.

In order to guarantee full compliance with specific and predetermined environmental parameters ($T = 20$ °C and $RH < 20$ %) and limit the presence of undesired phenomena, the devices (manipulator, orientation platform and vision system) will be stored inside a double-glazed container where temperature and humidity will be controlled by means of Peltier modules and silica gels.

Peltier modules represent the best solution to constrain temperature into a limited range since they can act either as cooling or heating systems by simply inverting the electric current direction. Moreover, when working as cooling systems the coupled heat-sink at the cold side of the module, kept at low temperatures by conduction, contributes to decrease the presence of humidity in the air by condensing it.

Figure 10 shows a preliminary layout for the test bed; the pick up pallet and the release pyramid are mounted in such positions in order to occupy the required area inside the manipulator's workspace.

8. Conclusions

The article has described the activities under development for the construction and optimization of an automated robotized cell for manipulation and assembly of submillimetric objects.

In order to obtain this result, major importance has been given and will be given to the prototyping of a fully automatized workcell that will execute a complete assembly task in challenging working conditions. The correct behavior of the single devices first and of the overall workcell then is demanded to each research unit. For this reason hardware and software interfaces between the different mechanisms and systems are being constantly improved and an efficient coordination of the research activities is mandatory.

Focusing on each unit's work, high performance devices like the micromanipulator and the orientation platform have been designed and will be built soon. Moreover, different solutions for the grasping have been considered and are being tested by means of innovative vision systems. At the end of the project all these components will be gathered together in a workcell. This workcell will be thermally isolated in order to guarantee full control of temperature and humidity, since at the mini-scale changes of these parameters can not be neglected.

After positioning and interfacing all the devices inside the same environment the test bed will be practically able to perform the desired task by manipulating and assembling 3D micro-objects. The possibility to collect and analyze significant performance indices will prove the correctness of the adopted approach for the research activity.

Acknowledgement

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