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Design of a miniaturized work-cell for micro-manipulation

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SUMMARY. The paper describes the design and development of a miniaturised workcell devoted to the robotized micro manipulation and assembly of extremely small components, jointly carried out by the University of Brescia, University of Bergamo, University of Ancona and the Institute of Industrial Technologies and Automation of the Italian National Research Council in the framework of the project PRIN2009 MM&A, funded by MIUR. Besides analyzing theoretical and practical aspects related to the design of the work cell components (positioning and orienting devices, grippers, vision and control systems), an automated test bed for the assembly of micro pieces whose typical dimension belongs to the submillimeter scale range has been implemented. The perspective is to contribute to the realization of general automatic production systems at the moment absent for objects of these dimensions.

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 and reliability and to reduce costs [1]. 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, obtained at the expense of system cost and complexity;
- the downscaling of conventional assembly solutions that loses effectiveness as part dimensions shrink, due to the predominance of superficial over volume forces;
- the identification of the appropriate gripper: the effect of adhesive forces acting between the gripper and the part may affect the correct part grasping and release;
- the measurement of the absolute position of parts and tools by vision systems is difficult to achieve, due to the reduced field of view and depth of field as the resolution increases.

Despite all these problems, in the last decade, miniaturization has spread out in all the consumer oriented products. Together with MEMS and MOEMS, other microproducts, called hybrid, have been proposed. They present a 3D geometry and are made of a number of components, each 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, first developed the concept of "Microfactory", indicating a miniaturized and reconfigurable system for the production of microproducts [2]. After twenty years the microfactory paradigm is well-known although not widely implemented neither in the research nor industrial fields.

The purpose of the presented research activity is to contribute to the realization of general automatic systems for the production of micro parts, developing and implementing:

- methodologies for the analysis, synthesis and design of meso/mini manipulators able to accurately and precisely position parts with overall dimensions of about 500 microns;
- methodologies and strategies for the micro parts 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 work-cell calibration;
- methodologies and strategies, based on vision systems, for robot and work-cell monitoring and supervising.

In detail, the project aims to develop: innovative micro grippers; 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 research will be proved by the assembly of a benchmark: a pyramid showing holes with different shapes on its faces, through which compatible pieces are inserted by a micromanipulator. The pyramid is correctly oriented by an orientation platform. 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 complexity of the manual assembly process and the related low productivity of a mass production approach, in the realization of hybrid 3D complex microproducts. The specifications of the objects to be assembled are defined using criteria of representativeness of the various categories of micro parts. Components with different materials, dimensions, shapes, qualities of the surfaces and masses are considered, including for instance: optical fibers, glass and metal micro-spheres with diameters ranging from 300 to 800 microns, ultra small SMD electronics components like resistors or capacitors.

The identification of the manufacturing tolerances takes into account the technological constraints of the available micro-manufacturing processes. 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.

2 THE MINI WORK-CELL

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 work-cell and the above mentioned methodologies and strategies are implemented and validated in

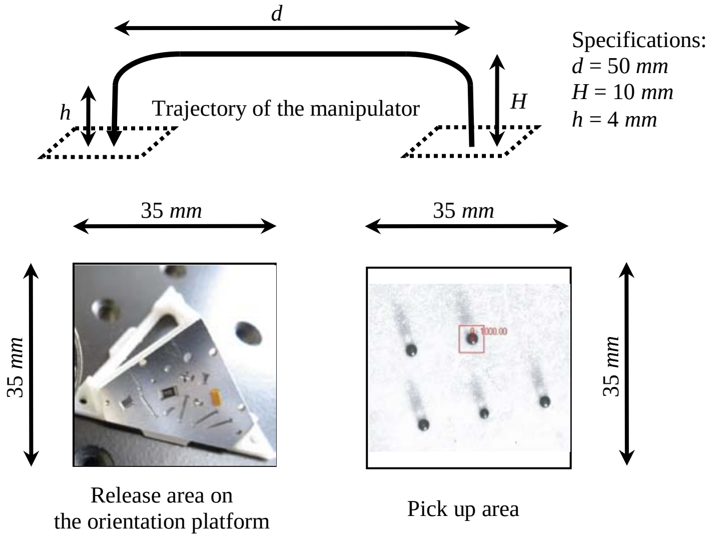


Figure 1: Sketch of the pick up and release working areas and trajectory of the manipulator.

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 the defined micro-assembly tasks.

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 work-cell 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 1). A vision system identifies position and orientation of an object randomly placed in a micro pallet. Different pieces with different shapes and sizes will be selected from a predefined set.

A 4 DOF degrees of freedom manipulator grasps the object and inserts it into a pyramid whose correct orientation is assured by a 2 DOF orientation platform. A global number of 6 relative degrees of freedom guarantees the accomplishment of the task.

2.1 *Positioning system: the manipulator*

The positioning system must provide 4DOFs for the manipulation of the micro-parts: it must guarantees translational motion along three orthogonal axes (x, y and z) for the positioning in the Cartesian space and a rotation α around the z axis for the orientation (Shoenflies motion).

The basic design requirements for the positioning system can be summarized as follows:

- the shape of the manipulation workspace must contain a prismatic volume whose projection on the xy-plane is a rectangle 100x35 mm, and its extension along z direction is at least 20 mm;
- the manipulator repeatability on the xy-plane should be less than 10 micron, while its resolution should be around 1 micron.
- considering the dynamic performance, the robot should execute a pick-and-place test cycle (10/50/10) with a cycle time of *1s* for the rated payload of *10g*, while for the maximum payload (*100g*) the prescribed cycle time is about *10s*.

Based on the required specifications, after analyzing several industrial and research microrobots [3,4], the kinematics structure of the micromanipulator was selected. The chosen kinematic architecture presents a hybrid structure: 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.

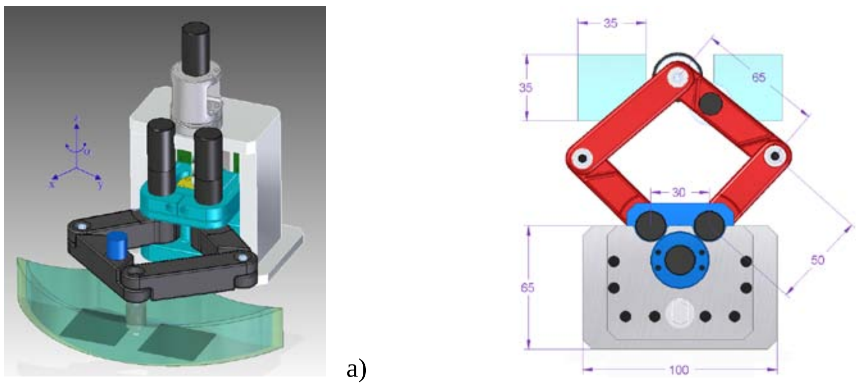
Firstly, the most suitable methods for the kinematics and dynamic synthesis of the selected manipulator and on the integration of the driving systems into the mechanical frame has been developed. To this end, several software tools for the synthesis and optimization of the micromanipulator have been realized. The simulation code allows to monitor several kinematic and dynamic performance indices. For example, it is possible to calculate some local and global dexterity indices such as the condition number *k* of the jacobian matrix J of the system and a kinematic manipulability measure defined as the square root of the minimum eigenvalue of JJ^T. Moreover, assigning the mass distribution of the system, it was possible to compute the torque exerted to the joints and other synthetic indices such as a dynamic manipulability measure [5].

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.

Thanks to these simulation tools, the kinematics and dynamic synthesis of the micromanipulator have been carried out and a preliminary prototype of the hybrid manipulator has been realized. Figure 2 depicts the virtual prototype and Figure 3 shows the physical prototype. The base frame of the manipulator prototype is made of aluminium, while the other parts, are made of "Vero White" (rigid opaque photopolymer) and fabricated in rapid prototyping.

The parallel structure is actuated, at the active joints, by two Faulhaber brushless DC motors (model 1628-T024B) combined with planetary gearbox with reduction ratio 66:1.

The rotation of the end effector around the z axis is driven by a Faulhaber brushless DC motor (model 1226-T012B**)** coupled with a planetary reducer (gear ratio 16:1).



a) b)

Figure 2: Virtual prototype of the 4-DOF. a) micromanipulator and its working space. b) Top view of the manipulator and its main dimensions

Figure 3: two views of the manipulator's physical prototype

Finally, a Faulhaber brushless DC motor (model 1628-T024B) drives a NSK micro ball screw (pitch 1*mm*), which is integrated in the base frame of the manipulator. In this way the z-axis is a serial axis that moves the whole parallel structure in z direction.

For the control of the manipulator four Faulhaber motion controller with CANopen interface have been selected, the control program has been written in C++ and has been developed on a real-time framework cooperating with the Linux kernel (Xenomai).

At the present stage of the research the manipulator prototype is being used to test the control algorithms and to verify the performance of the system. Simultaneously, using FEM analysis, new manipulator arms made of aluminum alloy are being designed in order to optimize the weight of the parallel structure and to limit the vertical deflection.

2.2 *Orienting system: orientation platform*

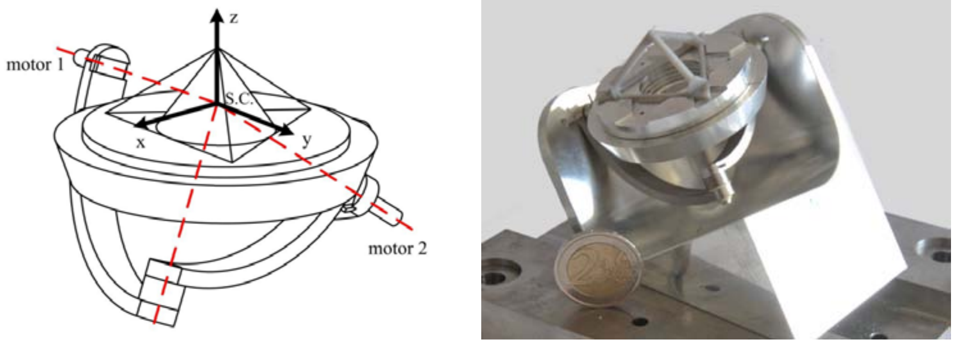
During the assembly tasks a 2-DOF pointing device must guarantee the correct parallelism between pins and holes; therefore a mini orientation platform has been conceived, responding to the following requirements:

- 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 platform was inspired to typical parallel kinematic structures, with the advantage of fixing the motors to the ground.

Starting from the basic idea of a spherical five-bar linkage [6,7] 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.



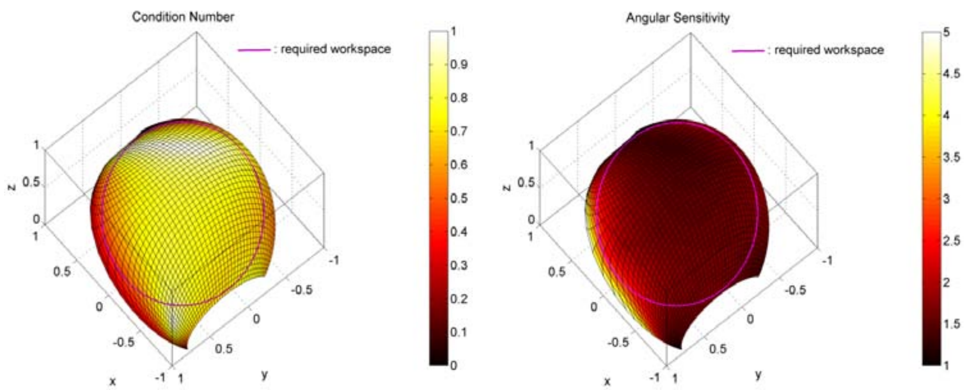
a) b)

Figure 4: 2-DOF orientation platform: a) optimized kinematic architecture; b) first prototype.

The optimized kinematic structure is represented in Figure 4a, while Figure 4b shows the first prototype of the platform.

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 5, 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 5a). Figure 5b 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 $5\cdot10^{-3}$ degrees (resulting from a 256 counts encoder and a gearbox with a reduction of 279), the maximum end-effector resolution inside the required workspace is of about $1.5\cdot10^{-2}$ degrees.



a) b)

Figure 5: a) Condition Number over the workspace; b) Angular sensitivity (ratio between encoder resolution and platform global rotation angle) over the workspace.

2.3 *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 with respect to gravity and mass related forces [8]. 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 manipulating macrocomponents. The release phase is 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 gripper and component, and between component and 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 [9,10].

Finally, vacuum grippers, based on the use of the force generated by the pressure difference between the gripper and the atmosphere, will be studied. They are often used at the macroscale for assembling delicate components, but their miniaturization can be obtained simply and cheaply connecting a cannula to a vacuum ejector.

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

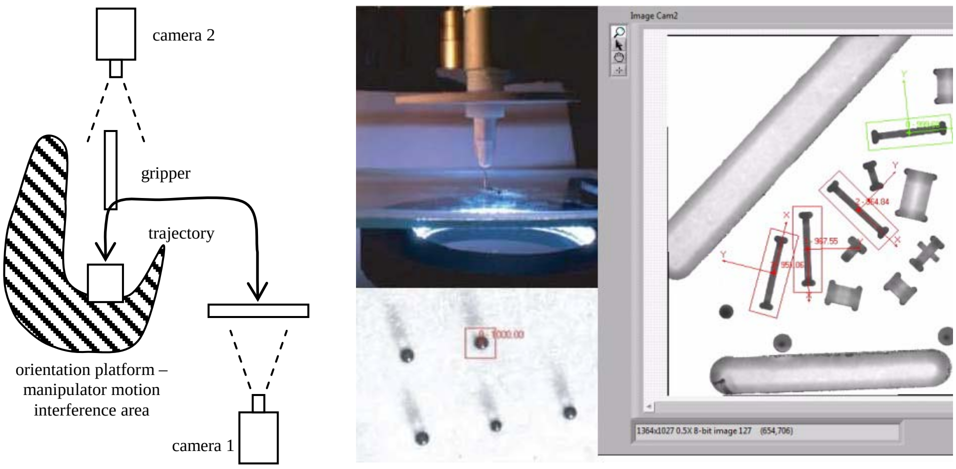
Thus far, the performance of two standard vacuum microgrippers (commercially available needles for dispensing) with respect to an innovative multi-lumen nozzle (designed by CNR-ITIA) has been critically analyzed. The benefits and limitations of these grippers, mainly in the releasing phase, have been highlighted and some solutions proposed [11].

In the same way as for the vacuum grippers, all the prototypes of microgrippers have been first 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.

2.4 *Vision system and calibration*

In order to develop a flexible workcell for micromanipulation and assembly, the use of vision systems can be convenient. 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.

The definition of the optimal vision system is an open issue particularly felt at the microscale, because both the part and environmental properties have to be more carefully and intently surveyed. Some of the important issues to be considered are the shape, the size, the materials, the colour, ... of the object to be observed and lightning, field of view, shape and size, ... of the video system. Many solutions can be found 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.



a) b)

Figure 6: a) Layout of the vision system setup; b) Example of localization and manipulation.

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 considered. A suitable lightning system will be chosen to cope with the critical aspects of image acquisition such as object reflection and colour of the parts.

In a workcell a robot and a vision system have to cooperate, therefore a robot calibration, a camera calibration and a robot-camera georeferencing are fundamental. Standard calibration methods present many limitations as the working scale decreases, 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 6a). 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 [12]. It allows to simultaneously calibrate the camera and georeference the camera with respect to the robot without using a calibration pattern.

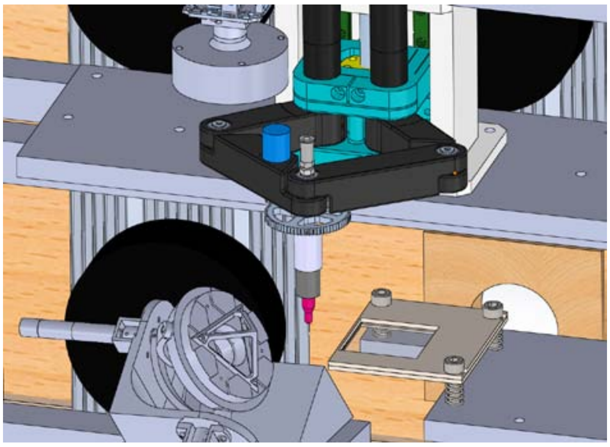
To build vision systems able to recognize the microcomponents to be manipulated and measure their position and orientation, a set of image processing and machine vision algorithms has been implemented, including geometric and pattern matching and blob analysis (Figure 6b).

3 INTEGRATION OF THE STAND-ALONE DEVICES INTO THE 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 devices will be integrated into a work-cell that will practically perform the desired task.

All the components of the work-cell will be programmed to execute the demonstrative task and tests will be performed together with measurements to check the proper tasks execution (object recognition, pose accuracy and repeatability, execution speed, time cycle, etc.).

a)



b)

Figure 7: a) The air conditioned box that will host the workcell; b) Detail of the working area.

In order to coordinate the movements of every mechanism, all the devices inside the work-cell will be equipped with independent controllers that will send alphanumeric strings to each other and to a “General controller” via Ethernet buses. A communication system based on the exchange of simple information and orders will be developed and point-to-point or trajectory movements will be considered to evaluate the performances of manipulator and/or the orientation platform.

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

The devices (manipulator, orientation platform and vision system) will be placed inside a double-glazed container where temperature and humidity will be controlled by means of Peltier modules and silica gels. This solution, shown in Figure 7a, guarantees full compliance with specific and predetermined environmental parameters (T = 20 °C and RH < 20 %) and limits the presence of undesired phenomena. In fact, Peltier modules represent an interesting technology 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 7b shows the 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.

4 CONCLUSIONS

The article describes the activities under development for the construction and optimization of an automated robotized cell for the manipulation and assembly of micro 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 built and will be integrated 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 the devices inside the same environment the test bed will be able to perform the desired task by assembling 3D micro-objects. The possibility to collect and analyze significant performance indices will prove the correctness of the adopted approach.

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