Manipulation of microcomponents using vacuum grippers

G. Fontana[1], S. Ruggeri[2], C. Pagano[1], I. Fassi[1], G. Legnani[2]

[1]*Institute of Industrial Technologies and Automation, National research Council, Italy*
E-mail: *gianmauro.fontana@itia.cnr.it, claudia.pagano@itia.cnr.it,*
irene.fassi@itia.cnr.it

[2]*Department of Mechanical Engineering, University of Brescia, Italy*
E-mail: *serena.ruggeri@ing.unibs.it, giovanni.legnani@ing.unibs.it*

Keywords: Micro-handling, Micro-Robotics

SUMMARY. During the past decades several microproducts have been fabricated for a great variety of applications in the traditional fields, including the medical and biomedical sectors, automotive, aeronautics and aerospace, Information Technology and telecommunication as well as in more innovative areas, such as household appliances, entertainment and sport equipment.

Nevertheless, hybrid three dimensional micro products have still great difficulty in penetrating the market, mainly due to the limits of the fabrication processes that require manipulation and final assembly of microcomponents. These processes, being not yet automated, strongly affect the cost of products. Therefore, new market perspectives can be reached automating the assembly phase.

The main challenge is due to the new physical scenario that appears when dealing with the assembly of millimetric and sub-millimetric parts. Indeed, at the microscale the high surface to volume ratio leads to the predominance of the superficial forces (e.g. electrostatic, van der Waals and surface tension forces) over the gravitational force; this results in an unpredictable behaviour of the traditional manipulating mechanisms, whereas an efficient and precise control of the grasp and release of thousands of microscopic and fragile parts is required. For this reason the downscaling of traditional handling strategies and the development of new handling techniques require further studies. Several solutions can be found in literature, with their advantages and limitations, i.e.: friction and jaw microgrippers, magnetic and electrical fields used to levitate objects, adhesive grippers exploiting capillary force. Also vacuum grippers can be miniaturized. Due to their intrinsic simplicity, vacuum grippers are very cheap and appear a promising solution for industrial applications, if some improvements are carried out.

In this context, an experimental setup for the automatic manipulation of microcomponents through some vacuum grippers was developed. Moreover, an innovative design of a nozzle for a vacuum gripper was fabricated and tested, comparing its performance with traditional needles. The design was conceived in order to reduce the frequency of occlusions of the nozzle and handle a wide range of particles. The tests described in this paper concern mainly the success and the precision of the release of objects from the gripper. Indeed, this is one the crucial aspect of micromanipulation because microparts tend to stick to the gripper preventing the successful performance of manipulation tasks.

1 INTRODUCTION

The majority of microsystems are currently fabricated by semiconductor-based manufacturing techniques, taking advantage of the consolidate experience gained from the fabrication of integrated circuits. More recently, a variety of emergent products (e.g. microresonators, radio frequency devices, drug delivery systems, chemical and biochemical sensors) requires components made of non semiconductor material in order to increase the performance and functionalities of the whole system. These components have to be made of metal, plastic and ceramic, which need appropriate fabrication processes and have to be assembled with each other or with semiconductor structures. The assembled systems are referred to as hybrid MEMS and are required in an increasing number of applications, where semiconductors do not fulfil all the specifications of the products. Nevertheless, their fabrication technologies are not yet sophisticated enough, and hybrid devices are still very expensive. Undeniably, one of the most crucial steps for the fabrication of hybrid MEMS is the assembling procedure, which can affect up to the 80% of the total cost of the product. Indeed, due to the high surface to volume ratio of microcomponents, superficial forces are predominant and the manipulation of microparts significantly differs from that of macroscopic devices. For this reason, the downscaling of standard assembling procedures at the microlevel is infeasible or inefficient and many operations have to be done manually [1].

Many issues can affect one or more of the three main manipulation phases (grasp, handling, release) and have to be taken into account during the design of the microgripping systems. Due to the charging effects, the parts move into their energetically most favourable configuration and this results in an uncontrolled grasping or release. Moreover, due the adhesion forces objects stick to the gripper preventing the release that is not anymore facilitated by the gravitational force due to the reduced weight.

In the literature, several solutions to these manipulation problems can be found, including hybrid-type grippers where two principles are integrated in order to reduce the adhesive force during the release [2], grippers based on physical principles peculiar of the microscale in order to control and exploit the adhesive forces [3][4], and handling systems without physical contacts between the gripper and the component, in order to avoid stiction during the release [5]. Among the strategies proposed for the micromanipulation there are: phase transition [6][7], magnetic [5], van der Waals [8], electrostatic [3][9], adhesive and capillary interactions [4][10]-[16], suction [17][18], and laser [19]. Each of these solutions has its own advantages and drawbacks, mainly concerning the cost, accuracy, repeatability, compliancy, versatility and complexity.

One of the strategies downsized from the macroworld is the use of the force generated by the pressure difference between the gripper and the atmosphere. Indeed, vacuum grippers are very common in the assembly of fragile macrocomponents and can be easily miniaturised. They can be very cheap as consist mainly of a micropipette connected to a vacuum pump. However, both the gripper and the part need to have smooth surfaces to prevent air leakage. Moreover, like all the contact grippers at the microscale, the adhesion forces significantly affect the release so that the precise positioning is difficult to achieve. This is the reason why some expedients for the release of microcomponents have been proposed. For instance, a short pressure pulse can be applied to assist the release of the microcomponent, even if it affects the accuracy of the positioning [17]. The adhesion due to the electrostatic force can be reduced coating the glass pipette for the suction with a conductive layer of gold connected to the ground [20].

In this paper, an experimental setup devoted to the automatic manipulation of microcomponents is introduced and preliminary experiments on the grasping and releasing of parts are described and discussed. The performance of various vacuum grippers is critically analysed and the limitations of these grippers, mainly in the releasing phase, are highlighted and some solutions proposed.

Indeed, beside the adhesion force, such as electrostatic, van der Waals and capillary forces, once the components adhere to the gripper without leakages the depression remains even when the vacuum pump is switched off. For this reason the experiments were carried out using two strategies in order to achieve the release, i.e. the inertial force and the positive pressure.

2 EXPERIMENTAL SETUP

A suitable experimental setup (Figure 1) able to move the parts and measure their position in the working area was designed.

2.1 *The work-cell for micromanipulation*

The work-cell is equipped with a Mitsubishi Electric RP-1AH robot (1). It is an ultra-compact robot with an arm mass of approximately 12 kg and an installation area equivalent to a sheet of paper ISO-216 A5 size. It presents a 5-joint closed link structure and 4 degrees of freedom with Schoenflies motion: 2 revolute joints for the positioning in the x-y working area, a third revolute joint for rotation and a prismatic joint for the z vertical end-effector motion. The robot is driven by AC servomotors (brakes on each axis) and the position detection is provided by absolute encoders. The communication is provided with Ethernet interface through TCP/IP protocol. The operating limits are 150x105 mm^2 with a vertical stroke of 30 mm. The repeatability is ±5 microns in the x-y plane, ±10 microns for the vertical motion and ±0.02° for the end-effector rotation.

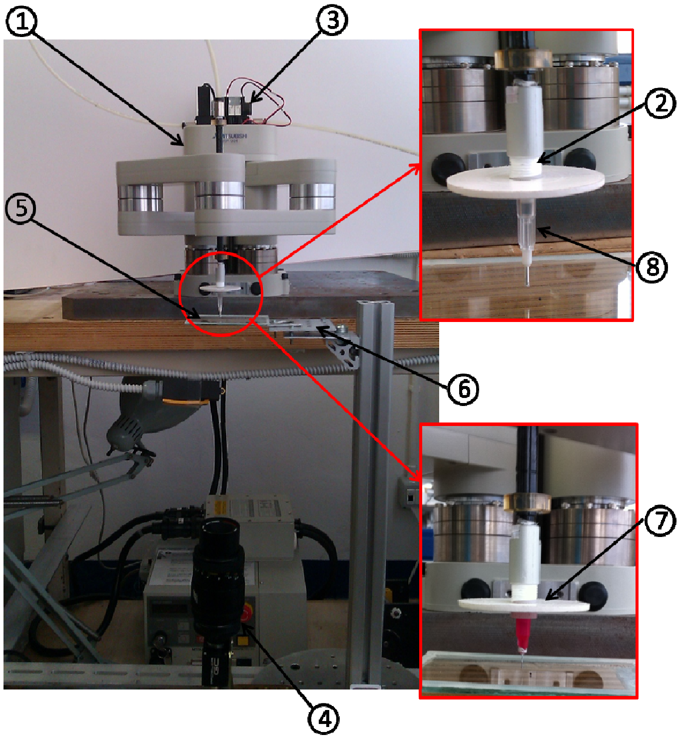


Figure 1: Experimental setup.

A smart and standard mechanical interface (2) was realized in order to facilitate the tool change. It was directly connected to the bottom part of the hollow screw constituting the third and fourth axis of the robot. In this way the cavity of the screw was exploited, avoiding the use of pipes near to the gripping components.

The vacuum generation system was a critical part of the setup, mainly during the releasing phase. Two vacuum generation systems were employed. The former consisted of an air compressor, a FRL (Filter Regulator Lubricator) group, a 5/2 double solenoid electropneumatic valve mounted on the top of the robot arm and a piINLINE® Micro Ti vacuum ejector installed directly on the hose near the suction point. The latter used the same air compressor and FRL group, but was equipped with a piCOMPACT10 vacuum ejector (3). This ejector is based on a COAX® cartridge Bi03-2 and integrates a vacuum sensor and two normally closed solenoid valves, one for the supply and one for the release. The latter and more complex generation system was needed to assist the release with a positive pressure.

The measurements of the position of the parts in the focal plane were performed by a suitably chosen vision system (4). An Allied GC2450 camera (see Table 1 for specifications) was combined with a Voigtländer macro lens (Table 2). In this condition, the field of view was 16.3x13.5 mm^2 with a spatial resolution of 6.6 microns.

Manufacturer	Allied
Model	GC2450
Resolution	2448 x 2050
Sensor Type	Sony ICX625 CCD, Progressive scan
Sensor Size	Type 2/3
Pixel Size (µm)	3.45 x 3.45
Frame Rate at Full Resolution	15 fps
Mono/Color	Mono
Video Output Type	Gigabit Ethernet (GigE Vision)

Table 1. Camera specifications.

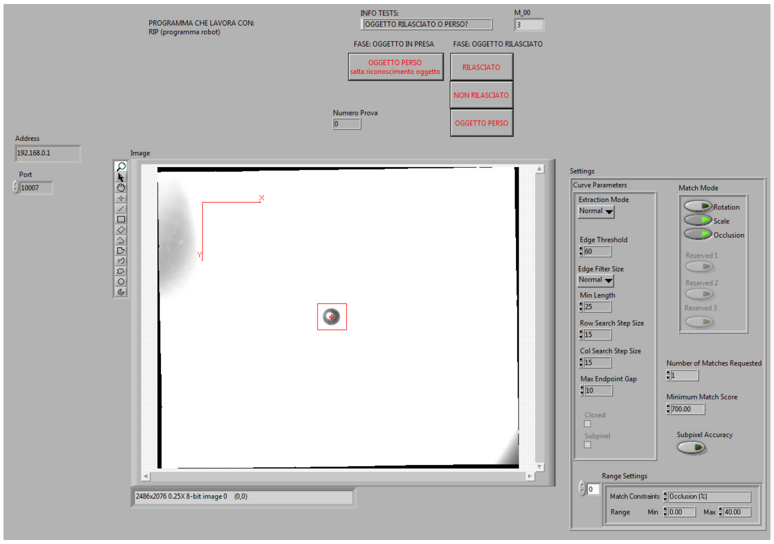
Manufacturer	Voigtländer
Model	Macro Dynar AF 100 mm f/3.5
Focal Length	100 mm
Aperture Ratio	1:3,5
Lens Construction	4 groups, 5 elements
Angle of view	24 °
Closest distance	0,43 m
Diameter	51 mm
Mount	M 39-Mount
Filter Size	49 mm

Table 2. Lens specifications.

The parts to be picked and released lied on a transparent glass substrate (5). The camera, fixed on a rigid structure below the robot working area, view from the bottom the end-effector. The glass substrate was mounted on an adjustable orientation platform (6) in order to assure its planarity and avoid the influence of the substrate inclination.

An opportune lighting system is essential for the detection, robust recognition and reliable measurement, thus a diffuse illumination of the scene was adopted, making the disturbance of the environment light negligible. The end-effector is also equipped with a contrast panel (7) to obtain better images.

The camera and the robot were calibrated in order to allow the automatic part detection for the grasp and after the release. Thus, a suitable vision algorithm was developed in LabVIEW® for a complete calibration of the manipulation cell, compensating for perspective, distortion and spatial referencing errors. Moreover, a set of vision functions and image processing algorithms were implemented, including a robust pattern matching algorithm for the detection of the parts in the field of view (Figure 2) and the elaboration of the displacement measurements. The data exchange between the robot controller and the LabVIEW programs running on a personal computer were handled and synchronized.



PROGRAMMA CHE LAVORA CON:
RIP (programma robot)

INFO TESTS: OGGETTO RILASCIATO O PERSO?
M_00: 3
Numero Prova: 0
Address: 192.168.0.1
Port: 10007

2486x2076 0.25X 8-bit image 0 (0,0)

Settings
Curve Parameters
Extraction Mode: Normal
Edge Threshold: 60
Edge Filter Size: Normal
Min Length: 25
Row Search Step Size: 15
Col Search Step Size: 15
Max Endpoint Gap: 10
Closed ☐
Subpixel ☐

Match Mode: Rotation, Scale, Occlusion, Reserved 1, Reserved 2, Reserved 3
Number of Matches Requested: 1
Minimum Match Score: 700.00
Subpixel Accuracy

Range Settings: 0
Match Constraints: Occlusion (%)
Range Min: 0.00 Max: 40.00

Figure 2: Screen of the Graphical User Interface of the pattern matching algorithm.

2.2 *The gripping tools*

The experiments were performed in order to compare the performance of two standard vacuum microgrippers (commercially available needles for dispensing, Figure 3a) with respect to an innovative multi-lumen nozzle (Figure 3b).

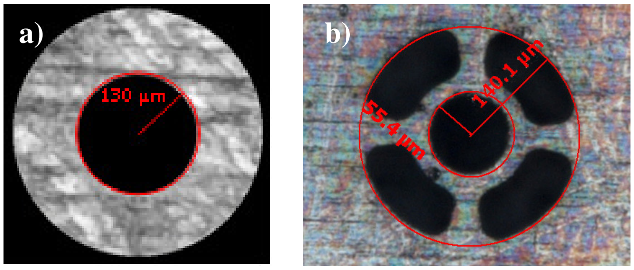


Figure 3: SEM images (bottom view) of: a) Needle type gripper; b) Nozzle type gripper.

In literature only few studies concerning the optimal dimensions of a vacuum microgripper depending upon the size of the components are available [17]. It has been demonstrated that the optimal diameter of the tip of the gripper is in the range of 25% to 50% of the part size.

In the case of the nozzle two main radii can be identified (Figure 3b). It has a central circular hole with radius equal to 55.4 microns and an external circle, that circumscribes the internal hole and the other four holes, with radius equal to 140.1 microns. This geometry was conceived with the purpose of manipulating a wider range of components, avoiding the need of changing the gripper during the manipulation of components with different sizes and geometries. The nozzle should be able to perform like a needle with dimension equal to its internal radius and a needle with dimension equal to its external one at the same time. Keeping that in mind, the performance of the nozzle was compared with the performance of two needles with internal diameters of 100 and 260 microns respectively.

3 EXPERIMENTAL PROCEDURES

The setup previously introduced was used to carry out pick and place tasks. Repetitive tests of the grasping and releasing of microcomponents were carried on. The initial tests showed that the results depended on the boundary conditions, for example the complexity of the trajectory of the robot during the handling of the components. A movement just along the z axis of the robot led to an easier release than a movement along two axes. Therefore, a trajectory similar to the path of a real pick and place operation was adopted for the tests.

For these preliminary experiments, the performance of each gripper was assessed using spheres with different diameters: 0.8 mm and 1.2 mm.

For each sphere, the test cycle consisted of 30 repetitions. Every repetition was the sequence of a pick and release operation, carried out as follows:

a. The camera took an image of the sphere on the substrate.
b. The vision algorithms allowed the recognition of the sphere in the field of view and the calculus of the x-y position of the centre of mass of the sphere (with respect to the reference frame of the robot base).
c. The position information was sent to the robot, which moved to bring the gripper over the sphere.
d. The robot controller switched on the vacuum pump.
e. The gripper picked the sphere by the vacuum technique.
f. The robot arm moved along the robot z and y directions, as executing a pick and place task, and, then, went back to a fixed position, keeping negative pressure in the gripper.
g. The camera took a second picture of the picked sphere, calculated its position and stored it in memory.
h. The vacuum pump was switched off to release the part.
i. In order to facilitate the sphere release one the following strategies was applied:
    1. the robot moved brusquely 2 mm upwards;
    2. the controller activated the release valve applying a positive pressure.
j. A third picture of the released sphere was taken by the camera.
k. The algorithms provided for the calculus of the x-y position of the centre of mass of the released sphere, which was stored for subsequent elaboration.

The feeding pressure was 2 bar, the vacuum flow was 0.04 Nl/s and the execution time of the tests was approximately 12 seconds. For the two grippers, these values were set to be the same in both cases. The step (i) describes the procedures adopted for the release. Indeed, due to the depression and the adhesion forces the release did not occur spontaneously when the vacuum pump was switched off. For this reason two strategies were tested to achieve the release: exploiting the inertial force of the sphere (i.1.) or the positive pressure (i.2.).

The environmental conditions were kept constant during all the tests: the temperature was 24 °C and the relative humidity 25%. Given the size of the manipulated objects, a clean room environment was not necessary.

4 RESULTS AND DISCUSSION

All the collected data was then processed. For each test cycle the accuracy (AC) and the repeatability (RP) were calculated according to standard ISO 9283. Although this standard is defined for the performance of manipulators, it was assumed significant also in this context.

The accuracy is defined as the distance between the target position and the barycentre of the cloud of the actual achieved positions, while the repeatability is defined as the statistical positional deviation from the average. The non-releasing percentage was also considered.

The smallest needle (internal diameter 100 microns) was tested with both the spheres, but its dimension was so small that it grasped the component only if in contact. Therefore, since the contact could damage the component and the gripper, a setup with an appropriate feedback, should be developed in the future to allow a deeper investigation. For this reason, in the following, the term needle will refer to the needle with internal diameter equal to 260 microns.

In Table 3 the comparison of the performance of the nozzle and the needle using the inertial force for the release is shown. The results showed that the nozzle achieves lower percentage of release of the biggest sphere. This is probably due to the superficial force contribution of the area of the nozzle between the central hole and the external ones. The opposite is true for the smallest sphere; in this case the nozzle achieves a greater number of releases. This might be due to a smaller surface contact of the nozzle. Indeed, the surface contact between the needle and the sphere is always the same, regardless the dimension of the sphere. Instead, in the case of the nozzle, it is likely that the contact surface is smaller for the smallest sphere than for the biggest one, where all the external circle is probably in contact with the sphere. This could also be the reason why the nozzle showed a higher probability of releasing the smallest sphere compared to the biggest one.

Release by inertial force		Sphere Dimension [mm]					
		1.2			0.8		
		AC [mm]	RP [mm]	Release [%]	AC [mm]	RP [mm]	Release [%]
Gripper type	Needle	0.175	5.094	96.67	0.775	4.992	43.33
	Nozzle	0.402	2.791	40.00	0.383	3.053	70.00

Table 3: Accuracy, repeatability and release percentage of the two spheres by the two grippers using the inertial force.

Concerning the precision of the positioning, no great difference can be found for the release of each of the two spheres, regardless the type of gripper (Table 3). In the case of the needle the accuracy value is high, as well as the repeatability value. Therefore, even when the percentage of the release is very high the accuracy of the positioning is unacceptable for any precise application. A more positive scenario appears with the use of the nozzle, even if the results are still too inadequate for a microprecision manipulation. It is likely that the procedure can be improved in order to reduce the energy of the sphere after the release. This could reduce the displacement of the sphere after the detachment from the gripper. Nevertheless, all in all, as expected and suggested by the literature, this release strategy seems to be not suitable for precise manipulation.

In order to achieve better results an alternative strategy for the release was tested. It consists in assisting the release with a small positive pressure. The parameters that control the blow were optimized for each case, since preliminary tests showed that it is strongly dependent on the gripper and the size of the sphere. The results of the release achieved with this strategy are summarized in Table 4 and graphically represented in Figure 4.

Release by positive pressure		Sphere Dimension [mm]					
		1.2			0.8		
		AC [mm]	RP [mm]	Release [%]	AC [mm]	RP [mm]	Release [%]
Gripper type	Needle	0.026	0.263	90.00	0.027	0.199	100.00
	Nozzle	0.030	0.330	96.67	0.098	0.589	56.67

Table 4: Accuracy, repeatability and release percentage of the two spheres by the two grippers using the positive pressure.

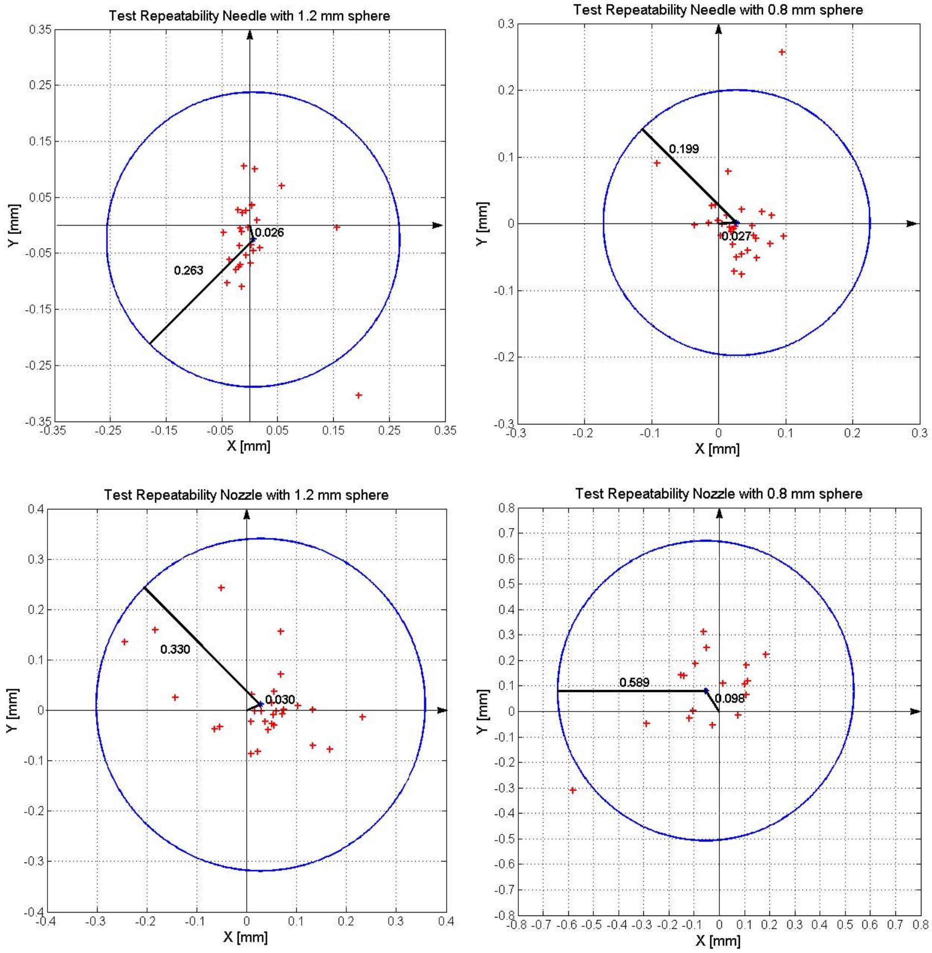


Figure 4: Dispersion plots: the radius of the circle represents the repeatability and the distance between the centre of the circumference and the origin of the axes represents the accuracy.

This strategy allowed the achievement of a better accuracy when the simple needle was used. The manipulation of both the spheres with the needle was successful in the great majority of the experiments (100% and 90% of release).

The success of the experiments seemed to be significantly influenced by the chosen parameters, including the entity of the depression for the grasp and of the positive pressure for the release. A threshold of values, which allows to achieve a high percentage of release and a great accuracy of the positioning was in some cases not found, mainly because of the rough regulation of the vacuum pump. In these cases, the experiments were done, trying to improve the precision rather than the success of the release. This strategy was preferred considering the future implementation of a control system able to indicate whether the release occurred or not. In any application such a system should be easily implementable, and preferable than dealing with a warranted but not precise release.

This issue occurred in the test of the nozzle and the small sphere, for which the achieved release percentage was 60% (Table 4). In fact the release achieved with the nozzle seemed to be more unpredictable than the release of the needle. This might be due to the complex shape of the nozzle, so that uncontrolled air flows through its five holes could occur.

5 CONCLUSIONS

An experimental setup based on a robot, a vacuum generator system and a vision system was designed and developed. It allowed the automatic manipulation of microcomponents with a variety of vacuum grippers. The experiments were carried out comparing the performance of a standard vacuum gripper (a standard dispending needle) and a multi-lumen nozzle in grasping and releasing microspheres.

Two strategies were tested in order to achieve a correct and precise release, one based on the inertial force of the sphere and the other on the positive pressure. The percentage of release is significantly improved using the second strategy, even though the procedure for the optimization of the parameters is much longer.

In the case of the needle also the accuracy of the release was improved using the positive pressure release strategy, whereas the nozzle worked quite the same, probably due to uncontrolled air flows through its five holes. The experiments showed that the performance of a traditional needle was higher than that of the nozzle. However, the nozzle seemed to be more flexible in handling components of various dimensions, whilst the needle size has to be chosen depending on the component dimensions.

Deeper research will be carried out on the nozzle, in order to understand the behaviour showed during the release with positive pressure, developing also some theoretical and numerical models. This will also help to identify if for suitably dimensions of the spheres the external holes can work as a mean of auto-centring of the sphere after the release.

References

[1] Van Brussel H. et al., “Assembly of Microsystems”, *Annals of the CIRP*, 49(2), 451-472 (2000).

[2] Chen T. et al., “A hybrid-type electrostatically driven microgripper with an integrated vacuum tool”, Sensors and Actuators A: Physical, 158(2), 320-327 (2010).

[3] Hesselbach J. et al., “Centering electrostatic microgripper and magazines for microassembly tasks”, in Proc. of SPIE, Microrobotics and Microassembly III, Newton, USA, 4568, 270-277, Oct 29-30 (1999).

[4] Biganzoli F., Fassi, I., Pagano C., “Development of a gripping system based on capillary force”, in Proc. of 6th IEEE ISATP, Montreal, Canada, July 19-21 (2005).

[5] Gosse C. and Croquette V., “Magnetic tweezers: Micromanipulation and force measurement at the molecular level”, Biophys. J., 82(6), 3314–3329 (2002).
[6] Kochan, A., “European project develops ice gripper for micro-sized components”, Assembly Automation, 17(2), 114-115 (1997).
[7] El-Khouy M., “Ice gripper handles microsized component”, Design News, Sept 8, 1998,
[8] Feddema JT. et al., “Micro-assembly planning with van der Waals force”, in Proc. of the IEEE International Symposium on Assembly and Task Planning, 32-38, July 21-24 (1999).
[9] Enikov E.T., K.V. Lazarov, “Optically transparent gripper for microassembly”, SPIE, 4568, 40-49 (2001).
[10] Bark C., Binneboese T., “Gripping with low viscosity fluid”, in Proc. of IEEE Int. workshop on MEMS, 301-305 (1998).
[11] Fukuda A., “Adhesion-type Micro Endeffector for micromanipulation”, in Proc. of ICRA 1472-1477, 1997.
[12] Grutzeck H., L. Kiesewetter, “Downscaling of Adhesive and Capillary Grippers for Micro Assembly”, in Proc. of Micro System Technologies 98, 6th Int. Conf. On Micro Electro, Opto Mechanical Systems and Components, 237-242 (1998).
[13] Grutzeck H. et al., “Downscaling of grippers for micro assembly”, Microsystem Technologies, 8, 27–31 (2002).
[14] Obata K.J. et al., “A scheme for micro-manipulation based on capillary force”, J. Fluid Mech., 498, 113–121 (2004).
[15] Saito S. et al., “Capillary force with a concave probe-tip for micromanipulation”, Applied Physics Letters, 87(23), 234103-234103-3 (2005).
[16] Westkamper E. et al., “Adhesive Gripper - a new approach to handling MEMS”, in Proc. of Actuator, 100-103 (1996).
[17] Zesch, W, et al., “Vacuum tool for handling microobjects with a NanoRobot”, in Proc. of ICRA, 1761-1776 (1997).
[18] Arai et al., “Micro endeffector with micro pyramids and integrated piezoresistive force sensor”, in Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (1996).
[19] Rambin C.L., Warrington R.O., “Micro-assembly with a focused laser beam”, in Proc. of IEEE MEMS, 285- 290 (1994).
[20] Petrovic D. et al., “Gripping tools for handling and assembly of microcomponents”, in Proc. of 23rd Int. Conf. on Microelectronics, 1, 247–250 (2002).