4 dof Piezoelectric Microgripper Equipped with a Smart CMOS Camera

B. Tamadazte, *Member, IEEE*, M. Paindavoine, J. Agnus, V. Pétrini, and N. Le-Fort Piat, *Member, IEEE*.

***Abstract*—This paper deals with the design of a *micro-eye-in-hand* architecture. It consists of a smart camera embedded on a gripper. The camera is a high speed (10 000 fps) CMOS sensor of 64 × 64 pixels. Each pixel measures 35 μm × 35 μm and includes a photodiode, an amplifier, two storage capacitors, and an analog arithmetic unit. The gripper consists of a 4 dof (degrees-of-freedom) (*y*+, *y*-, *z*+, *z*-) microprehensile based on piezoelectric actuators.**

***Index Terms*—CMOS Sensor, Microgripper, Eye-in-Hand System, Micromanipulation, Microrobotics**

I. Overview

There is a growing interest in 3D complex hybrid MEMS (Micro Electro Mechanical Systems) and MOEMS (Micro Opto Electro Mechanical Systems) devices. They are used in a variety of domains: automotive, households, IT peripherals and bio-medical devices.

To obtain 3D MEMS, it is necessary to use microassembly processes. Two microassembly techniques exist in the literature: self-assembly and robotic assembly. In the latter, a robotic system combined with a microhandling system [1] and an imaging system are used to reach the same objective [2], [3], [4]. The vision sensors used in this case are mainly based on optical microscopes or conventional cameras associated to a high magnification objective-lens. This type of imaging systems has very inconvenient sizes and weights.

Traditionally, a camera can be used in a robot control loop with two types of architecture: eye-in-hand when the camera is rigidly mounted on the robot end-effectors and eye-to-hand when the camera observes the robot within its work space. In microrobotic applications, the eye-in-hand architecture is not possible because of the size and weight of an optical microscope although this configuration may have many interests in the case of vision feedback control [5]. The use of eye-in-hand system in microrobotic applications allows to solving many constraints related to the use of an optical microscope. Notable constraints are: the small depth-of-field (DOF), the small field-of-view (FOV), and the small working distance.

B. Tamadazte, J. Agnus, V. Pétrini, and N. Le-Fort Piat are with the FEMTO-ST Institute, UMR CNRS 6174-UFC/ENSMM/UTBM. 24 rue Alain Savary, 25000 Besançon, France. Corresponding e-mail : brahim.tamadazte@ens2m.fr. Phone: +33 (0)3 81 40 27 99.

M. Paindavoine is with LEAD-CNRS UMR 5022 - Borgogne University - Pôle AAFE - Esplanade Erasme. BP 21065, Dijon cedex, France.

This work is partially conducted with financial support from the project LEMAC from the PRES Bourgogne France-Comté.

Manuscript received ..., 2011; ...

This paper presents a new concept of a 4 dof microgripper equipped with a small and intelligent CMOS camera. This concept allows replacing the traditional cumbersome and expensive imaging system which equipped the traditional microassembly workcells. The embedded imaging system consists of a 64 × 64 pixels CMOS analog sensor with per pixel programmable processing element in a standard 0.35 μm double-poly quadruple metal-metal CMOS technology (refer to [6], for more details).

This paper is organized as follows: Section II presents the 4 dof piezoelectric-based gripping system and the CMOS camera characteristics. The final designed eye-in-hand system is presented in section III along with its integration on a robotic MEMS microassembly station. Section IV presents the obtained results of the eye-in-had system (i.e. the CMOS sensor and microgripper) characterization.

II. Developments

In this section, we present the developed 4 dof microprehensile system and the smart CMOS camera used to design the novel eye-in-hand system dedicated to MEMS manipulation and assembly tasks.

A. Piezoelectric microgripper

The gripper developed in our lab is used for handling. It has 4 dof and allows open-close motions as well as up-down motions. It is based on piezoelectric actuators which consist of two parallel piezoceramic PZT PIC 151 bimorphs (see Fig. 1). Each parallel bimorph is independent, and able to provide two uncoupled dof (details summarized in Table I). The piezoceramic bimorph contains two superimposed actuated 200 μm layers, to produce independent movements along ($y-$ and $y+$), and ($z-$ and $z+$) directions [7]. The shape of the microgripper's end-effectors can be adapted according to the type of the handled MEMS.

TABLE I
MOCC microgripper features.

Typical strokes	
open-close	320μm
up-down	200μm
Blocking forces	
open-close	$55mN$
up-down	$10mN$
Other characteristics	
High resolution	$\sim 10\ nm$
Speed	$\prec 10\ ms$

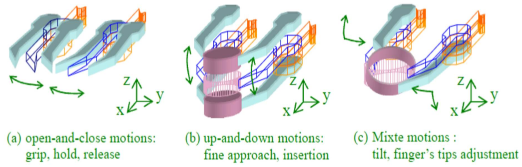

Fig. 1. Representation of the gripper functionalities.

TABLE II
CMOS SENSOR CHARACTERISTICS.

feature	size	feature	size
array size	64×64	transistors	160 000
chip size	11mm^2	transistors/pixel	38
pixel size	35×35μm^2	supply voltage	3.3V
fill factor	25 %	dyn. pwr consumption	110mW

Figure 1 represents draws of the functioning of developed gripper's dof, Fig. 1.(a) shows the *open-and-close* motions, also called in this paper $y-$ and $y+$ directions, used to grasp and release the handled micro-objects, Fig. 1.(b) illustrates the *up-down* motions, i.e. $z-$ and $z+$, directions used for fine displacements (insertion tasks) of the micro-object, and Fig. 1.(c) represents combined motions (e.g. $y+z+$ or $y+z-$ displacements) in order to adjust the space position of the grasped micro-object.

B. CMOS sensor

There are two primary types of electronic image sensors: Charge Coupled Devices (CCDs) and Complementary Metal Oxide Semiconductor (CMOS) sensors. CMOS imaging technology has become increasingly the major technology because of its several advantages such as a simple operation process, low fabrication cost and low power consumption.

In this paper, we have developed a smart CMOS camera based on the AMS CMOS 0.35 μm technology. The described sensor size is 64 $\times$ 64 pixels with a chip size of 11 mm^2 with 160 000 transistors (38 transistors per pixel and a pixel fill factor of around 25%) as depicted in the layout of a 4 pixels block in figure 2.

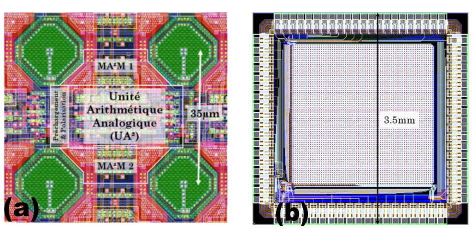

Fig. 2. (a) layout of 4 pixels and (b), full layout of the retina (64x64 pixels).

Figure 2 illustrates the mask design of the pixel (four metal, double poly), with its four related photodiodes. The center of the analog arithmetic unit ([**AM**]^2) is equidistant from the centers of the photodiodes. This has direct impact on the spatial noise sensor axis. It is obvious that for automatic micromanipulation of micro-object using vision-based techniques, the integration of hardware low-level image processing techniques inside the sensor will be an asset. Thus, various *in-situ* image processing had been integrated using local neighborhoods (such as spatial gradients, Sobel and Laplacian filters). The developed CMOS sensor characteristics are summarized in Table II.

III. EYE-IN-HAND DEVELOPED

As mentioned previously, the gripper end-effectors can be adapted to the type (i.e. size and shape) of the micro-objects to be manipulated. So, for a better functioning of the developed eye-in-hand system, it is necessary to be able to control the embedded camera position according to the gripper end-effectors. Thus, 2 dof have been added to the camera support: a linear stage x and an angular stage α (see, Fig. 4). These dof have a dual interest in our application. First, the adjustment of the translation and rotation stages allows a target visualization of the scene (i.e. the end-effectors tips, the MEMS handled, etc.). Second, this 2 dof allow a precise adjustment of the camera focus in order to get a sharp view of the scene.

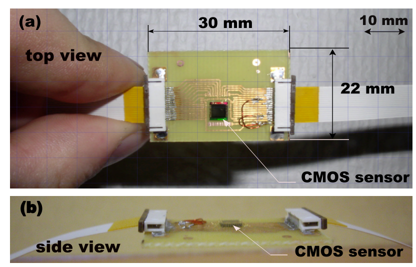

Fig. 3. Photography showing the final connection of the developed CMOS camera and integrated in the PCB support.

Figure 3.(a) shows a top view of the CMOS sensor when it is connected to the support measuring 30 mm $\times$ 22 mm $\times$ 1 mm (length, width and depth, respectively). Figure 3.(b) illustrates the side view of the connected sensor. It can be seen that it is very compact.

The eye-in-hand system presented in this paper can solve the following constraints related to the use of the optical microscopy in the MEMS microassembly workcells: traditional integration problem of optical microscopes in microrobotic stations, possibility to use an eye-in-hand architecture in MEMS manipulation and assembly processes, and solve the problem of the weak depth-of-field often encountered using optical microscopes in MEMS assembly stations.

Figure 5 illustrates the 5 dof home made MEMS microassembly workcell including the developed eye-in-hand system where (a) represents the 4dof piezoelectric-based gripper equipped with nickel end-effectors, (b) shows the embedded smart CMOS camera and its support, (c) represents the 2 dof (zϕ) micromanipulator, (d) shows the silicon micro-objects to be visualized and manipulated, (e) illustrates the compliant micro-objects support, and (f) represents the 3 dof (xyθ) positioning platform.

IV. VALIDATION

A. Gripper performances

The performances of the developed gripper are tested using a home-made 5 dof MEMS microassembly station (Fig.5).

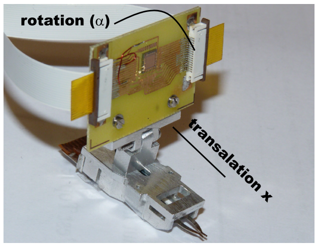

Fig. 4. Final developed eye-in-hand system.

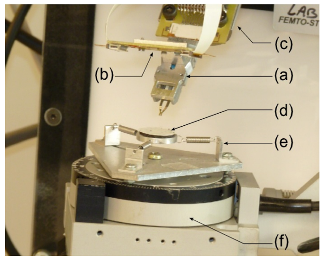

Fig. 5. Integration of the developed system into a MEMS microassembly station.

Two methods to control the gripper dof are studied: *all-or-none* method, especially, in the case of manipulation of rigid micro-objects and *closed-loop* approach using vision-based control law adequate for biological cell manipulation. In the case of the first type of micro-objects, a control strategy which consists of a *look-and-move* vision based control law is implemented to validate the developed active gripper. The obtained accuracies in the different dof are of 1.36 μm (average estimation for ten micromanipulation cycles) with a standard deviation of 0.34 μm (refer to [8], for more details).

B. Sensor characteristics

The developed CMOS sensor was tested in terms of conversion gain, sensitivity, fixed pattern and thermal reset noises, and dynamic range. The obtained results are summarized in Table III.

TABLE III
CHARACTERIZATION OF THE CMOS SENSOR.

dynamic gain	68 dB
thermal reset noise	68 μV RMS
fixed pattern noise	225 μV RMS
sensitivity	0.15 V/lux.s
conversion gain	54μV/e$^-$ RMS

Figure 6 shows experimental image results. Figure 6.(a) shows an image acquired at 10 000 fps (integration time of 100 seconds). Except for amplification of the photodiodes signal, no other processing is performed on this raw image. Figure 6.(b)-(d) show different images with pixel-level image processing at a frame rate of about 2500 fps. From left to right, horizontal and vertical Sobel filter and Laplacian operator images are displayed. Some of these image processing algorithms imply a dynamic reconfiguration of the coefficients. We can note that there is no energy spent for transferring information from one level of processing to another because only a frame acquisition is needed before the image processing take place. In order to estimate the quality of our embedded image processing approach, we have compared results of horizontal and vertical Sobel and Laplacian operators obtained with our chip and with digital operators implemented on a computer. In each case, the image processing is applied on real images obtained by our chip. For the comparison of the results, we have evaluated the likelihood between the resulting images by using the cross correlation coefficient. In our case, this coefficient is 93.2% on average which demonstrates that the analog arithmetic unit has good performance compared to external operators implemented on a computer.

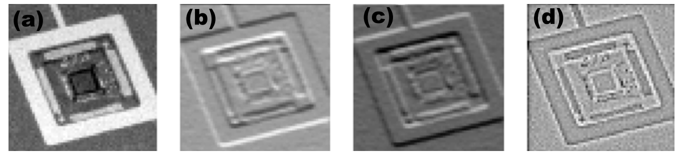

Fig. 6. (a) raw image at 10 000 fps, (b) output Sobel horizontal image, (c) output Sobel vertical image, and output Laplacian image.

V. CONCLUSION

In this paper, we have presented a novel smart eye-in-hand system for MEMS microassembly applications. This system was developed to solve many problems or constraints related to the use of the optical microscopes in MEMS microassembly processes. First, to surpass these constraints, we have designed a 64 $\times$ 64 pixels smart microcamera based on CMOS technology with a high speed acquisition (10 000 frames per second). With basic image processing techniques, the maximal frame rate is about 5000 fps. Each pixel measures 35 μm $\times$ 35 μm and includes a photodiode, an amplifier, two storage capacitors, and an analog arithmetic unit. Some image processing techniques as spatial gradients, Sobel operator and second-order detector (Laplacian) have been implemented. Second, a novel version of the home made 4 dof piezoelectric-based microprehensile have been designed in order to integrate the developed smart camera.

The next step of our research concern the implementation of more sophisticated image processing operators, e.g. recognition and vision-based operations like the integration of low level visual servoing control laws (*look-and-move* techniques), directly in the developed CMOS sensor.

REFERENCES

[1] F. Beyeler, A. Neild, S. Oberti, D. Bell, Y. Sun, J. Dual, and B. Nelson, "Monolithically fabricated micro-gripper with integrated force sensor for manipulating micro-objects and biological cells aligned in an ultrasonic field," *IEEE/ASME JMEMS*, vol. 16, no. 1, pp. 7–15, Feb. 2007.

[2] C. W. Dechev, N. and and J. Mills, "Microassembly of 3D microstructures using a compliant, passive microgripper," *IEEE/ASME JMEMS*, vol. 13, no. 2, pp. 176–189, Apr. 2004.

[3] B. Donald, C. Levey, and I. Paprotny, "Planar microassembly by parallel actuation of MEMS microrobots," *IEEE/ASME JMEMS*, vol. 17, no. 4, pp. 789 – 808, Aug. 2008.

[4] M. Probst, C. Hurzeler, R. Borer, and B. Nelson, "A microassembly system for the flexible assembly of hybrid robotic MEMS devices," *Int. J. of Optomechatronics*, vol. 3, no. 2, pp. 69–90, Apr. 2009.

[5] B. Tamadazte, E. Marchand, S. Dembélé, and N. Le Fort-Piat, "CAD model-based tracking and 3D visual-based control for MEMS microassembly," *IJRR*, vol. 29, pp. 1416–1434, Sep. 2010.

[6] R. Mosqueron, j. Dubois, and M. Paindavoine, "High-speed smart camera with high resolution," *J. of Embedded Syst., S.I. "Embedded Vision System"*, vol. 2007, no. ID 24163, p. 16, Dec. 2007.

[7] J. Agnus, D. Hériban, M. Gauthier, and V. Ptrini, "Silicon end-effectors for microgripping tasks," *Precision Engineering*, vol. 33, 542–548, 2009.

[8] B. Tamadazte, N. Le Fort-Piat, and S. Dembélé, "Robotic Micromanipulation and Microassembly Using Monoview and Multiscale Visual Servoing," *IEEE/ASME T-MECH*, vol. 16, no. 2, pp. 277–287, Apr. 2011.