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Characterization and control of a monolithically fabricated bistable module for microrobotic applications

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Abstract—**Microrobots are widely used for microassembly and micromanipulation. However achieving performances compatible with the work in the microworld requires the use of bulky and expensive systems for measurement, signal processing and real time control. In this paper, we present the characterization and the control of a bistable module that can be used to build microrobots. This bistable module is fabricated monolithically using microfabrication technology. It offers two stable and blocked positions. High resolutions can be reached using this approach. Static and dynamic characteristics of the bistable module are studied and an open-loop control strategy is proposed in order to switch smoothly from one position to the other. The presented bistable module is the basic module for building digital microrobots.**

I. INTRODUCTION

MICROROBOTS are widely used for microassembly and micromanipulation of artificial and biological objects with dimensions ranging from 1 micrometer to 1 millimeter. Resolution and accuracy in the submillimetric range are needed in order to interact with micrometer sized objects. Methods and strategies used to build conventional robots are often not applicable in the microworld due to scale-down effects [1]. New mechatronic approaches, new actuators and new robot kinematics are required.

In the literature, a lot of works concerning the design and the fabrication of smart microgrippers as microrobot end-effectors to perform micromanipulation tasks are presented. The designed microgrippers usually consist of an amplification mechanism which permits to amplify the motion induced by microactuators. This approach allows reaching a high resolution [2]. Other designs of microrobots include fabrication of mobile microrobots with micrometer dimensions. B.R. Donald designed a mobile microrobot with 200µm in length [3]. US National Institute Standards and Technology (NIST) proposed a mobile microrobotics challenges aiming to design microrobots no bigger than 600 micrometers. Many designs and realizations have been made since 2007 [4]. This kind of microrobots presents micrometric dimensions compatible with the working environment and high resolutions can be reached. However, since these microrobots are rarely equipped with sensors, closed-loop control requires expensive external systems for measurement, signal processing and real time control. Moreover, these systems present difficulties in terms of installation and fixing [5][6][7].

The existing microrobots are mainly based on the use of active materials to actuate microrobots, which gives adequate performances such as high resolution and fast response. Piezoelectric materials [8][9][10][11], shape memory alloys (SMA) [12][13][14] and active polymers [15][16][17] have been successfully used to actuate various types of microrobots. However, despite their intrinsic high resolution, these materials present some drawbacks, making both the modeling and efficient control big challenges. They present complex, nonlinear and sometimes non stationary behaviors [18][19]. Although the closed-loop control can avoid these problems, the integration of small sensors into the microrobot is very difficult [20][21].

To get over these difficulties, we proposed a new kind of microrobots named digital microrobots [23]. These new microrobots are based on bistable modules. Each module offers two stable and blocked positions. Desired positions can be obtained by switching the bistable modules. Sensors are not needed because bistable modules offer two known positions. This approach associated with microfabrication technology allows building monolithic microrobots that can be controlled in open-loop. Prototypes of bistable modules have already been fabricated. In this paper, we focus on the characterization and the control of a bistable module. Static and dynamic performances including switching from one position to the other are tested. A control strategy is proposed to obtain perfomances compatible with the requirements of microrobotics. This paper is organized as follows: in section two, the bistable module is presented. Sections three and four are dedicated to the static and dynamic performances. In section five a control strategy is proposed and the last section concludes this paper.

II. PRESENTATION OF A BISTABLE MODULE

A bistable module is the basic element for building a digital microrobot. It includes a bistable mechanism, thermal actuators and two stop blocks (see **Fig. 1**) [23]. In **Fig. 1**-a, a typical bistable mechanism is shown. No external energy is needed to maintain the mechanism in its state. Two pairs of thermal actuators were designed to switch the bistable mechanism (see **Fig. 1**-b).

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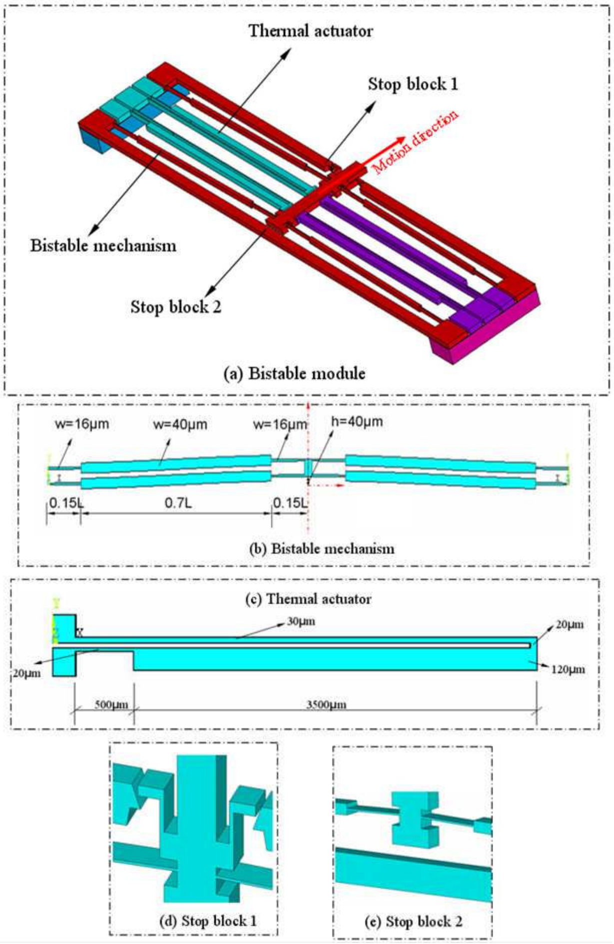

Fig. 1. Overall view of a bistable module and details. (a) Bistable mechanism (b) Thermal actuator (c) Stop block 1 (d) Stop block 2.

To obtain a blocked force compatible with microrobotics applications (between 200µN and 1.5mN), and a displacement of the bistable mechanism with micrometric resolution, taking into account the microfabrication limits of our clean room we proposed the dimensions shown in Fig. 1-b. The length of the whole structure is 8mm (in Fig. 1-b, L=4mm).

To move the bistable mechanism from a stable position to the other one, we designed two pairs of thermal actuators. The chosen dimensions of the thermal actuators enable to switch the bistable mechanism (Fig. 1-c).

To reach the desired blocked force and an accurate distance between the two stable positions, two stop blocks are designed. Stop block 2 (see Fig. 1-e) can be easily designed by putting a frame in front of the stable position. However, it is difficult to obtain a second blocked position because of the monolithic fabrication. A dedicated stop block (stop block 1) was designed. It allows obtaining a blocked force in the stable position (see Fig. 1-d).

Activation is required to put it in position. This bistable mechanism is fabricated using silicon on insulator (SOI) wafers with 100µm thick device layer (Young's modulus: 69Gpa), 300µm thick handle and 1µm sacrificial oxide layer. The handle layer is used to support the entire structure and the bistable structure is fabricated in the device layer (see **Fig. 2** and Fig. 3).

In Fig. 4, two stable positions are shown after the activation. The stable position 1 is now in the blocked state. It can be switched by thermal actuators between these two stable positions.

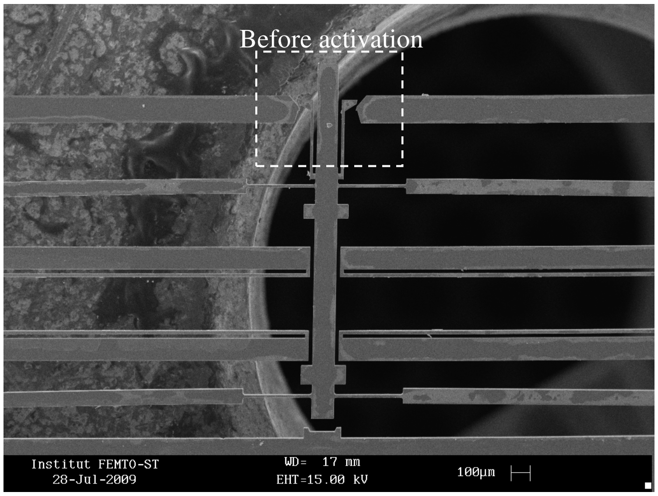

Fig. 2. SEM picture of a bistable module before activation.

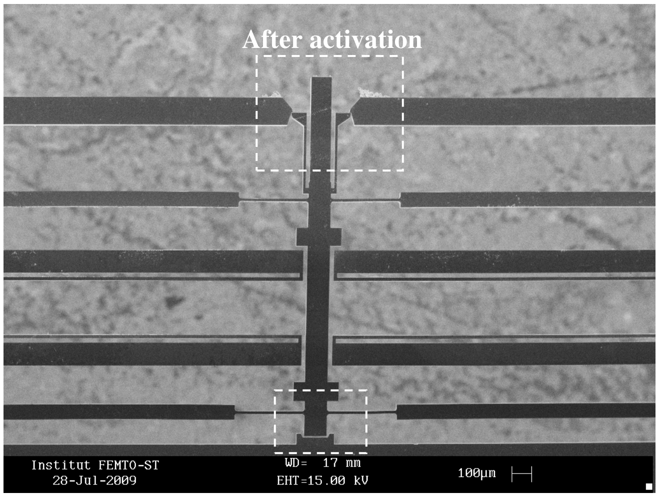

Fig. 3. SEM picture of a bistable module after activation.

Bistables modules with different distances between the stable positions were designed. According to the designed digital microrobot, the minimum distance defines the resolution of the microrobot. The resolution depends on the fabrication process.

I. STATIC CHARACTERISTICS

In order to study the static behavior of the bistable module, a commercial force sensing probe is used (see Fig. 5). The blockage force can be evaluated using this force sensor. The experimental set-up is shown in Fig. 5. An optical microscope is installed on the scene to observe the measurement. We move the force sensor to push the blocked bistable mechanism, when the bistable mechanism moves the blockage force is obtained.

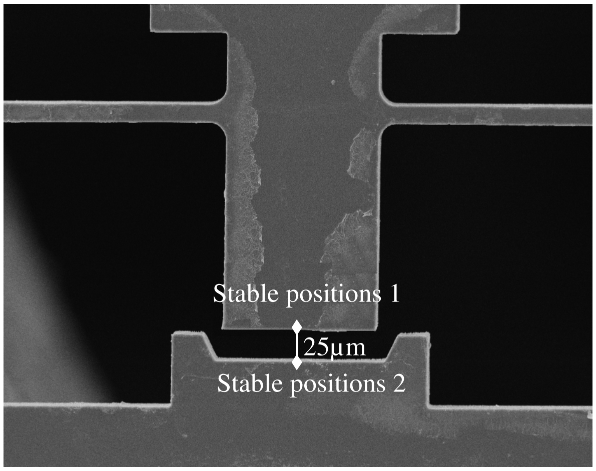

Fig. 4. Details of the two stable positions after activation.

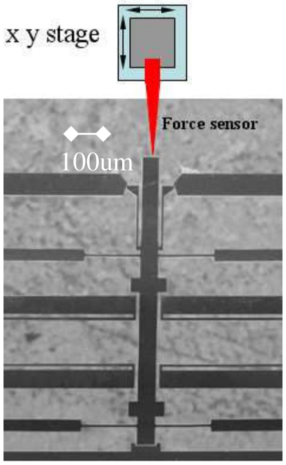

Fig. 5. Experimental set-up (a commercial force sensing probe (ST-S270) from FEMTO TOOLS with a sensitivity of 899.2 μN/V is used).

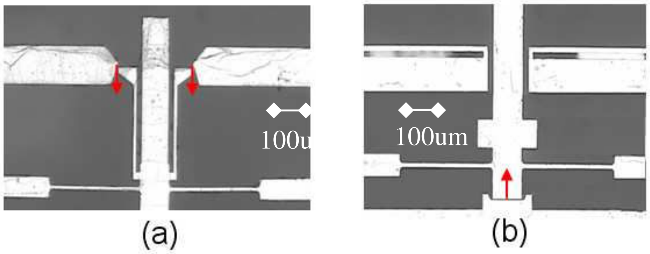

Fig. 6. (a) Blocked force in stable position 1 (b) Blocked force in stable position 2.

Modules with three different distances between the stable positions have been designed the measured blocked forces are shown in Table1.

II. DYNAMIC CHARACTERISTICS

Dynamic characteristics show duration, speed, accuracy and repeatability of state changes of a micro-positioning or microrobot system. We will study these characteristics of the bistable mechanism from a stable position to the other stable position in this section.

TABLE I

THE MEASURED BLOCKED FORCE OF THREE DIFFERENT DISTANCES.

Stop block	Distance between two positions	Measured blocked force
Module 1	7μm	212μN
Module 2	11.5μm	540μN
Module 3	25μm	1310μN

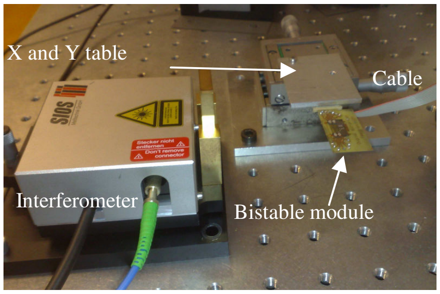

Fig. 7. Experimental set-up for bistable module.

For this measurement, the bistable modules are prepared for an in-plane measurement. We use a high resolution (10 nm) interferometer from SIOS Technology to test the dynamic response of bistable mechanism by measuring the displacement of the shuttle of a bistable module. All the test devices are mounted on an anti-vibration table (see Fig. 7).

The considered module has been activated in the blocked position 1 (see Fig. 8). Two switching transitions are studied. For the transition to stop block 2, we power the actuators (A2) and for the transition to stop block 1, the actuators (A1) are powered.

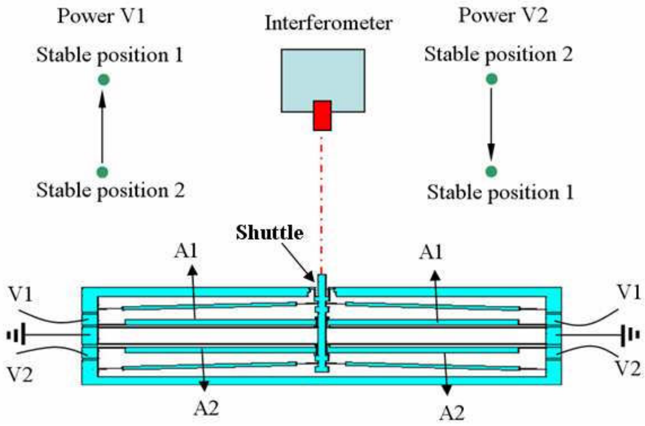

Fig. 8. Switching test using a high resolution interferometer.

A. Transition from stop block 1 to stop block 2

To switch from stable position 1 to stable position 2, the voltage is applied on the thermal actuators (A2). The interferometer detects the motion of the bistable mechanism. The result is shown in Fig. 9.

As a gap exists between the actuator and the bistable mechanism, they will be in contact after a delay. The bistable mechanism is switched when the voltage reaches 17V.

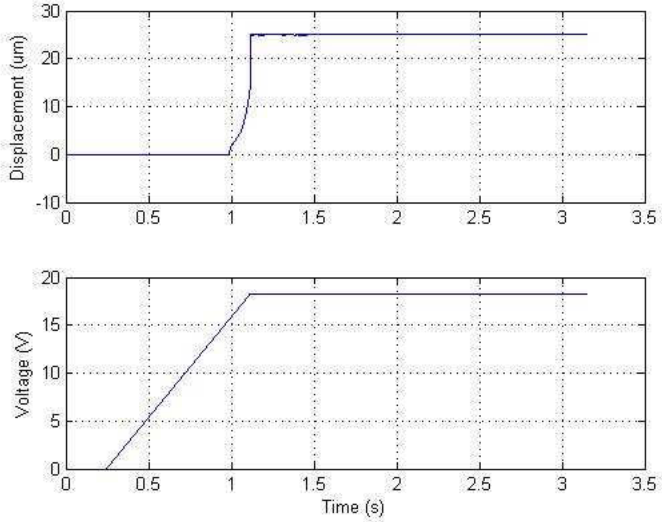

Fig. 9. Transition from stable position 1 to stable position 2.

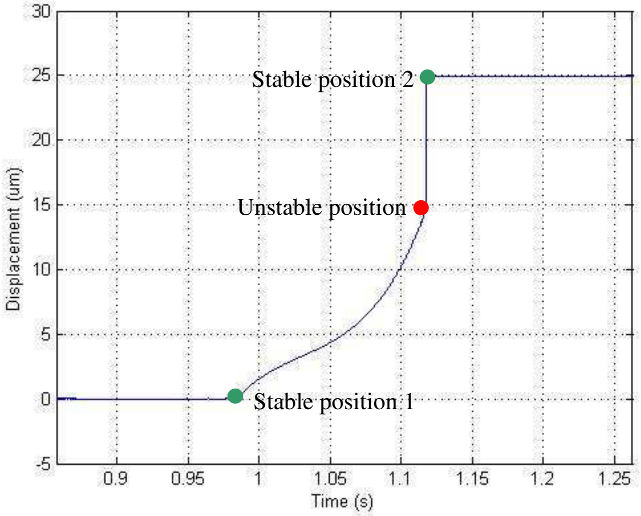

Fig. 10. Details of the transition to stable position 2.

In Fig. 10, the first phase from stable position 1 to unstable position (red point) is controlled by the actuators. The duration is about 117 ms for a displacement of 25 μm. The second phase is very fast compared to the first phase and it can be neglected. This transition does not present overshoot and vibrations. Since the final position is blocked by a stop block, the accuracy and repeatability are ensured. This result has been obtained on all the measurement tests.

B. Transition from stop block 2 to stop block 1

A ramp voltage is applied to the thermal actuators (A1) to actuate the bistable mechanism from stable position 2 to stable position 1. Fig. 11 shows the results.

As previously, since there is a gap between the actuator and the bistable mechanism, the contact is obtained after a delay. The bistable mechanism is switched when the applied voltage reaches 17V. In Fig. 12, the first phase (from the stable position 2 to unstable position) is similar to the transition from the stable position 1 to unstable position. However, during the second phase from unstable position to the stable position 1, overshoot appears. An overshoot of 4.5μm is measured (see Fig. 12).

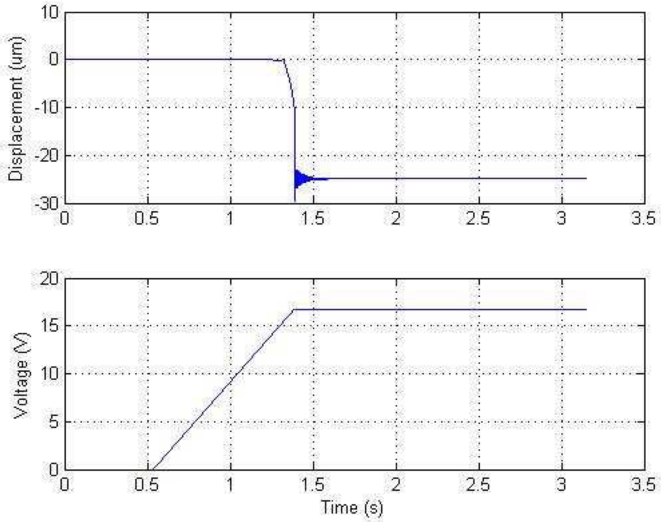

Fig. 11. Transition from stable position 2 to stable position 1.

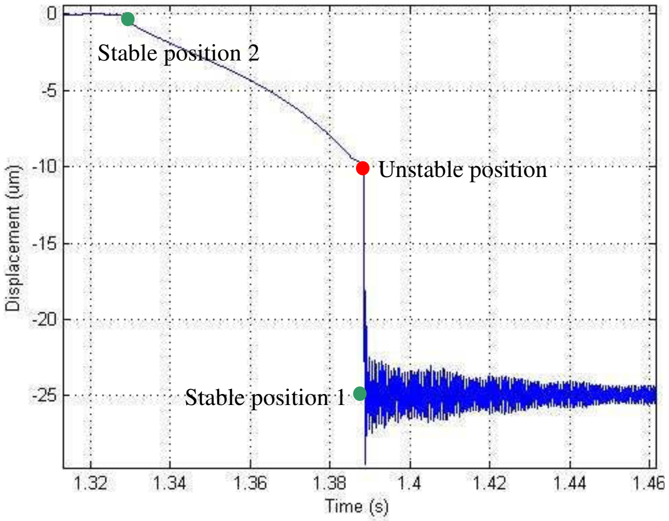

Fig. 12. Details of the transition to stable position 1.

Actuation time between the two stable positions almost depends on thermal actuators because the free motion of bistable mechanism from the unstable position to stable position is very fast and it can be ignored (see Fig. 12).

III. CONTROL STRATEGY

According to the results of the last section, the actuation of the bistable mechanism from stable position 2 to stable position 1 shows overshoot which is not suitable for microrobotics or micro-positioning. Indeed, the final position should not be exceeded. In order to control the switching and avoid the overshoot without feedback, we propose an open-loop control strategy to obtain a damped transition. The strategy is based on the use of two pairs of thermal actuators during switching operation. The principle is based on the use of one pair of thermal actuators (A2) to catch the bistable mechanism during the movement (see Fig. 13). We use the set-up described in Fig. 8 to make the experimentation.

The phase from the first stable position to the unstable position is controlled by actuator (A1) (see middle curve of Fig. 14). When the unstable position is reached (the time is at 1.69s), the first phase is finished.

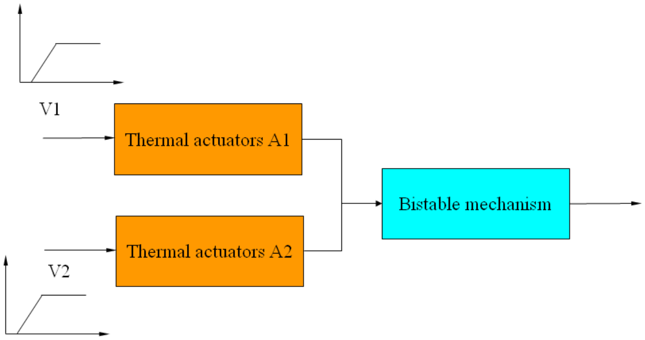

Fig. 13. Schematic of control system of a bistable module.

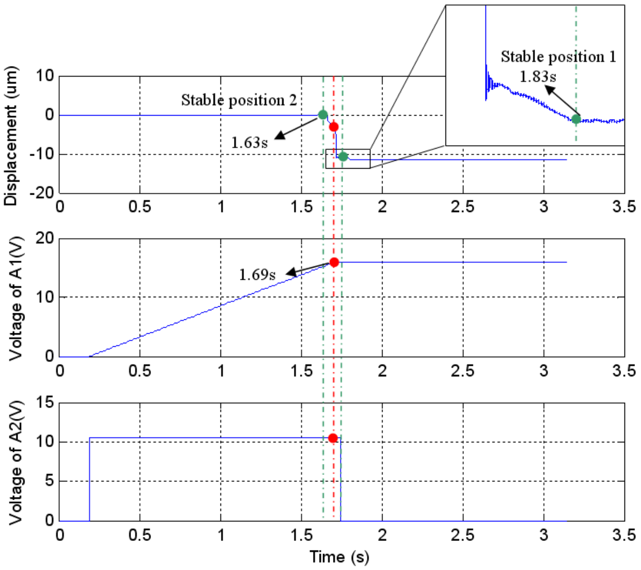

Fig. 14. Control sequences (Voltage A2 and Voltage A1 on the actuators) and the response of bistable mechanism.

The shuttle goes through the unstable position, and enters the second phase (from the unstable position to the other stable position). The actuators (A2) are used to control this phase (see bottom curve of Fig. 14). The bistable mechanism is maintained by the actuator (A2) and moved to the second stable position (see top curve of Fig. 14).

Fig. 15 shows the comparison between the switching with and without control. We can observe that the use of this control can reduce significantly the overshoot when the contact is established between the shuttle and the actuators. It does not present the overshoot in the final position. The whole switching time is about 205ms.

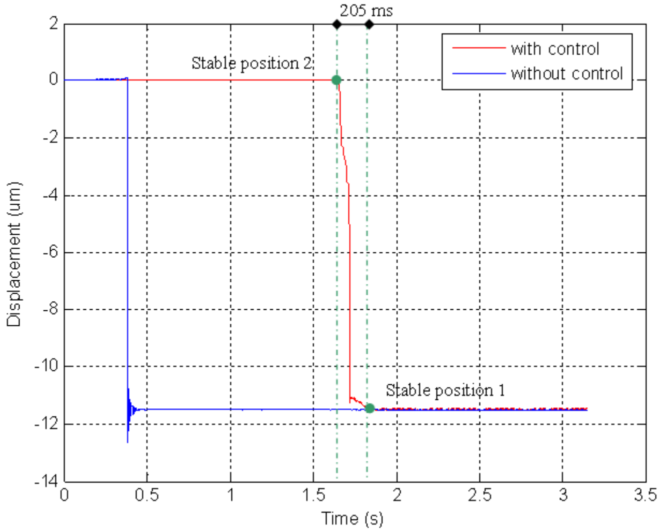

Fig. 15. Comparison between the transition with control and without control.

IV. CONCLUSION

After introducing the designed bistable module as the basic module for building digital microrobots, we presented the static and dynamic characterization of the module. The dynamic behavior of the mechanism for one transition revealed overshoot and vibrations. An open loop control strategy has been developed in order to improve the dynamic behavior. This strategy has significantly improved the dynamic behavior and the response is well damped with no overshoot. The general performances of the module are compatible with the requirements of micropositioning. The design and open loop control of a bistable module is a milestone for the development of digital microrobotics.

Future work will consist in the design and fabrication of complete monolithic robots using several bistable modules.

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