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Digital Microrobotics Based on Bistable Modules : Design of a non-redundant digital micropositioning robot

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***Abstract*— High precision manipulation becomes a recurrent need in micro or nanoscale. Microrobots based on active material were designed to perform micromanipulation tasks in various environments such as microrobotic stations or electronic microscopes (SEM, TEM). These active materials are used to generate proportional actuation, but show some drawbacks we want to avoid (non linearity, integration of sensors, . . .). In this paper we propose a new type of microrobot, called digital microrobot. It is based on the use of bistable modules (Fig. 1), and generates a discrete workspace. This microrobot can be used in open-loop mode and gets rid of bulky and expensive instruments and sensor integration. Moreover, no external energy is required to maintain the microrobot in a given position. The study presented in this paper is dedicated to the design of the robotic structure in order to generate a desired workspace.**

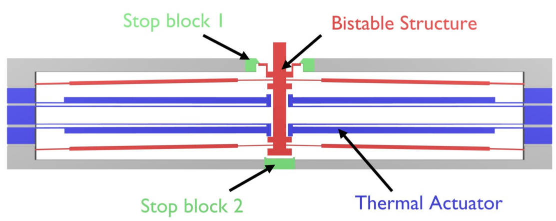

Fig. 1. Bistable Module

I. INTRODUCTION

With the fast development of microtechnologies during the last decades, several microrobots have been developed to interact with the MEMS (Micro Electro Mechanical Systems), and other micro-objects. Increasing accuracy and repeatability of these positioning systems was therefore formulated in the domain of microrobotics, in order to handle various tasks in the microworld. In particular for the manipulation of the micro-objects (whether artificial ones or biological ones), for the positioning and the characterization of these objects, or even for the micro-assembly of MEMS. These studies focus on two main points : design of grippers (hand effectors) to handle micro-objects, and design of the carrying microrobots (carrier) for the positioning of the gripper. Although studies of micro-grippers design have expanded widely, the studies concerning carriers was limited. Micro-grippers are becoming very powerful. They include several kinds of sensors ([1][2]) in order to manipulate objects with more safety, or to improve the releasing process ([3]). Current carriers created to manipulate very small objects, are often designed as the miniaturization of robots used in the mesoscale. This is why they face the same problems as traditional actuators such as friction, wear, backlash or lubrication. Several studies have nevertheless been done for the development of carriers.

Microrobotic community have adopted the active materials in order to actuate the micropositioning systems. These materials show much better capabilities in the microworld than the traditional actuators massively used in mesoscale robotics and manipulation tasks. Active materials actually present very high resolutions and are therefore mostly used for actuation and sensing. However, these active materials present some drawbacks which may be difficult to handle during the control process of the system. The behavior of such materials is very complex, presenting non linearity and sometimes non stationarity. These drawbacks make the modeling and thus the control of such actuators very difficult. Moreover, the sensors needed for the control are generally difficult to integrate, bulky and expensive instruments for signal processing and real-time operating.

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A. Binary Actuation

We propose a new concept of microrobot in order to overcome all these problems. This robot is based on discretely-actuated modules. An analogy can be made between continuous *vs.* binary manipulators and analog *vs.* digital circuits. In electronics, digital devices replaced many of their analog counterparts because of higher reliability and lower cost. Similar reasons motivates the conception of digital robots.

Discrete actuators have already been developed for a long time with the stepper motors. The control of these actuators became easier, but it also generated drawbacks already encountered with traditional actuators such as friction. That is why the use of control feedback is necessary. In order to generate a discrete workspace, we will use binary actuators that can be used in open-loop.

In the mesoscale, several binary-actuated robots have already been developed and showed very good performances compared to the commonly used continuous range of motion robots and positioners. The most known one is the variable geometry truss (VGT) manipulator which is a macroscopically serial manipulator composed of binary actuators. It was highly studied by Chirikjian since 1994 with his binary paradigm for robotic manipulators in [4]. This planar binary VGT manipulator consists of several cascaded modules. Each of them is composed of three binary actuators, resulting in eight discrete states (2^3). By adding modules on top of each other, the end effector of the manipulator can reach a very high number of discrete positions, revealing a highly-redundant workspace. An other well-known binary manipulator uses the same concept of three binary actuators by modules. It is the Binary Robotic Articulated Intelligent Device (BRAID) [7]. This is also a VGT manipulator like the previous one, but it can create a three dimensional workspace, and is aimed to be used in aerospace robotics.

In the microscale, several binary actuators have also been developed. They were mainly used as digital-to-analog converters ([8][9]), and showed very good accuracy and stability. They can be used as small linear micropositioners. For example, by including them inside MEMS, we become able to position several of the MEMS components such as micromirrors. Other binary micro-actuators were also used as electric relays in MEMS ([10]).

B. Bistable Module

To obtain a digital microrobot, our first work was to design the elementary module which can constitute the whole digital microrobot. This module is not a simple binary module, but a bistable module. Most of binary modules have two stable positions, but not two robust ones. Only one of the two positions generated is robust thanks to the use of stoppers.

Unlike these modules, bistable modules have two stable, robust and repeatable states. They furthermore do not need power supply while staying in one of the two positions used. The energy supply is only needed for switching states. This property of bistability induces very low power consumption, and enables the open-loop control of the system. The bistable module developed in [11] was furthermore improved compared to other bistable micro-actuators such as the one in [10], in order to improve its stability and strength.

Let us see how this bistable module works. It is a monolithic structures, of $2 \times 9\ mm^2$ in dimensions, and composed of three different elements (see Fig. 1) :

- one bistable structure
- two stop blocks
- two pairs of thermal actuators

The thermal actuators push forth and back the bistable structure whose displacement is limited by the stop blocks. These stop blocks furthermore induce a blocking force, guaranteeing the robustness of the two positions generated.

II. GLOBAL DESIGN OF THE ROBOTIC STRUCTURE

A. Fabrication Constraints

The objective is to create a monolithic microfabricated microrobot based on the use of bistable modules described previously. The bistable modules from which we will start building the microrobot have a very small thickness compared to its other dimensions. It is a $9\ mm$ width and $2\ mm$ height module with a maximum thickness of $500\ \mu m$. The microrobot will show a very thin architecture, resulting in a fragile structure. Even if this small thickness can be seen as a drawback, it is also one of the positive points of this architecture. Small thickness actually enables the robot to work in confined environments like microrobotic stations or Transmission Electronic Microscopes (TEM). In order to control the fragility of the structure, the stress generated inside the structure has to be check. It should not exceed the breakpoint (limit of the stress) of the material used. This stress has to be checked for the normal use of the robot (activation of modules) as well as for the manual handling of the structure (for instance while microfabricating it). The stress threshold we consider here is $1\ GPa$ for silicon.

Some constraints are directly linked to the bistable modules' properties. The first one concerns the dimensions of the module which are quite large compared to the generated displacement. The robotic structure has to be sufficiently large to include the modules, but can furthermore generate very small displacements. The second one is the force to which the module can resist. This bistable module was actually designed with the objective to be used in a robust robotic structure. Each module can undergo a force of $1.54\ mN$ before showing significant values of unwanted displacement. With the aim of maintaining the good behavior of the microrobot, the force applied onto the bistable modules should not exceed that blockage force.

The last constraints concern the kind of workspace we want the microrobot generates. The generated workspace, presents 2^n positions (n is the number of modules used in the microrobot). As this robot is designed to work in the microscale, the workspace will have a submicrometer resolution. The first robotic architecture we are going to build will generate a two dimensional displacement, that is why we consider a square workspace without any redundancy. Redundancy is indeed a prevalent property of digital robots. It is the cause of many difficulties for the trajectory planning and forward or inverse kinematics calculation.

B. Chosen Structure

These bistable modules can not be assembled on a serial way. Two main reasons lead us to this conclusion. The first one is the weight that each module induces on the other ones. Indeed while increasing the number of modules, the weight that every module will support increases as well and creates an opposition force to the displacement of the bistable structure. The second reason is the most binding one, it involves the connector wires of the modules. As these wires are quite big compared to the size of the modules' components, they can block several modules of the serial structure. These two reasons introduce forces that are in opposition to the force created by the thermal actuators of the module, and may prevent these modules from switching. They are very restrictive and will in the best case deteriorate the good behaviour of the robotic structure, but could probably block the displacement of the entire robot. We abandoned the concept of a serial structure for the robot, and focused on a parallel design for the robotic architecture. The parallel structure is actually very good because it provides a strong robotic structure that could handle heavy components. It is very well fixed to the base of the robot, facilitating the powering of all the bistable modules and does not generates any problems with the connector cables.

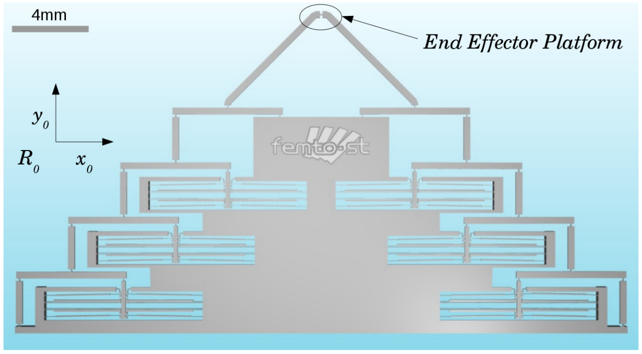

Fig. 2. CAD model of the digital microrobot with six bistable modules

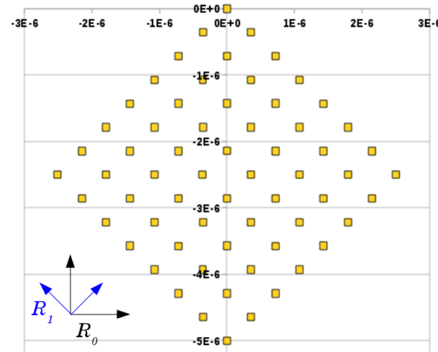

Fig. 3. Workspace generated by the robotic structure with 6 modules

We conceived a structure that fits all the constraints previously mentioned, and can furthermore use only modules of the same displacement, making the fabrication process much easier. All the bistable modules used generate a displacement of 10 μm. The proposed architecture was created in order to generate a two dimensional workspace. This first digital microrobot is composed of six bistable modules occupying an area of $4 \times 3\ cm^2$. A CAD model of the mechanical structure of this robot is represented on Fig. 2. All the bistable modules of this structure are generating the same displacement of 10 μm. The workspace generated (Fig. 3) is a square of 4 μm length. It contains 64 discrete positions (2^6), each of them are stable and robust. This workspace shows no redundancy, all these positions are distinct. They are furthermore equidistant in the two dimensions of the referential $\mathcal{R}_1$, with a separation of 505 nm. The referential $\mathcal{R}_1$ is the referential of the workspace (see Fig. 3), it is different from the referential of the structure $\mathcal{R}_0$ (see Fig. 2) by a rotation of $\frac{\pi}{4}$.

This structure consist in six bistable modules, but we can easily extend it to a higher number of modules (all of them always generating the same displacement between their two states). By doing so, we don't change the size of the workspace generated, but only increase its resolution. From a theoretic point of view (considering perfect revolute joints), each time we add one module to the structure, we improve the resolution by two in one dimension (one side of the square). The dimension in which the resolution is improved depends on the side of the structure on which the module is added. This means that if we have a structure with 10 bistable modules (5 on each side of the structure), the workspace generated will be a square of 4 μm length, that contains 1024 distinct points, all equidistant with a separation of 126.25 nm. Introducing a resolution four times better in the two dimensions than with only six bistable modules. All these results are valid for the case in which all the rotoid articulations are perfect.

The resolution reachable by this robot depends on the number of modules we add to it. The better resolution we can reach is limited by the size of the wafer on which the robot will be fabricated (the size of the wafer limits the number of modules we can add).

III. ROBOTIC ANALYSIS

Because of discrete and highly redundant workspace, calculation of the forward and inverse kinematics is generally difficult for digital robots. While several studies have been made in this domain in [5] and [6], they only consider the case of macroscopically serial manipulators presenting a hyper-redundant workspace. But, in the case we are presenting here, we have chosen a robotic architecture for which the kinematics calculation is simplified.

A. Forward Kinematics

The forward kinematics of this structure can be reduced to a simple form. For this calculation we consider the robot as a rigid structure with perfect rotoid articulations. As the size of the structure is very huge compared to the small displacements generated by the bistable modules (a ratio of 1000), the rotations considered are very small. All the trigonometric functions can then be linearized.

We define the position of the end effector by its coordinates x and y in the referential $\mathcal{R}_0$ of the structure (see Fig. 4). Equation 1 represents the forward geometric model of the microrobot.

$$\begin{bmatrix} x \\ y \end{bmatrix} = K \cdot \begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{4} & -1 & \frac{-1}{2} & \frac{-1}{4} \\ 1 & \frac{1}{2} & \frac{1}{4} & 1 & \frac{1}{2} & \frac{1}{4} \end{bmatrix} \cdot \begin{bmatrix} bl_1 \\ bl_2 \\ bl_3 \\ br_1 \\ br_2 \\ br_3 \end{bmatrix} \quad (1)$$

The constant K in (1) depends on the geometric parameters of the structure, namely the length and width of the beams and the displacement of the bistable modules. The $bl_i \in \{0; 1\}$ defines the state of the module i on the left side of the structure, and the $br_i \in \{0; 1\}$ is for the modules of the right side.

From a generic point of view, if we have N_1 modules on the left side (named bl_1 to bl_{N_1}), and N_2 modules on the right side of the structure (named br_1 to br_{N_2}), the forward kinematics can be written as in (2).

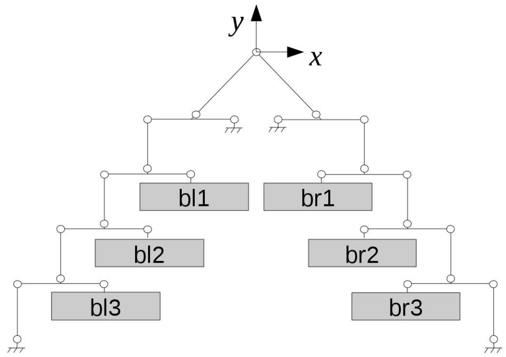

Fig. 4. kinematic model of the robotic structure

$$\begin{bmatrix} x \\ y \end{bmatrix} = K' \cdot \begin{bmatrix} \delta l_1 & \cdots & \frac{\delta l_{N_1}}{2^{N_1-1}} & -\delta r_1 & \cdots & \frac{-\delta r_{N_2}}{2^{N_2-1}} \\ \delta l_1 & \cdots & \frac{\delta l_{N_1}}{2^{N_1-1}} & \delta r_1 & \cdots & \frac{\delta r_{N_2}}{2^{N_2-1}} \end{bmatrix} \cdot \begin{bmatrix} bl_1 \\ \vdots \\ bl_{N_1} \\ br_1 \\ \vdots \\ br_{N_2} \end{bmatrix} \quad (2)$$

Where δl_i is the displacement generated by the bistable module number i on the left side of the structure, and δr_i is the displacement generated by the bistable module number i on the right side of the structure. The reader may notice that the constant K' is different from the previous constant K. Indeed, the displacement generated by each module (δl_i and δr_i which were the same for every module in the previous case) was included in the constant K.

The forward kinematics developed here is reduced to a matrix multiplication. It is a generic formulation of the forward kinematics that can easily be adapted to any architecture of the same type. One important thing to notice in this matrice is that the displacement generated on the end effector by one module is half the displacement generated by the previous module (on the same side of the structure). Thanks to this particularity, two different combination of modules cannot reach the same position. This induces a non-redundant equidistant workspace.

B. Inverse Kinematics

For digital robots, the inverse kinematic model calculation is quite difficult because we first have to know the exact location of every reachable positions, and find the position the closest to the desired one. The number of reachable positions is 2^n, where n is the number of actuators. This number n can easily exceed twenty, generating a huge list of positions. The difficulty of the calculation of the inverse kinematic model increases exponentially with the number of actuators. The redundancy property of the workspace make it even harder. But for the case we are dealing with now, the inverse kinematic model is quite easy to establish. Thanks to the particular configuration of this workspace, i.e. non-redundancy, square and uniform distribution.

For the inverse kinematics solution, we have to consider an other referential than the basis referential ($\mathcal{R}_0$). We will work on the referential of the workspace ($\mathcal{R}_1$). The difference between the referential of the workspace and the referential of the robot is only a rotation of $\frac{\pi}{4}$. We define the desired position of the end effector $\underline{X}_d$ by its components x_d and y_d in the referential of the workspace. We then need to know the resolution of the workspace. Two resolutions have to be known, the one on the x_1 axis (δ_x) and the one on the y_1 axis (δ_y).

The calculation of the inverse kinematic is composed of three steps for each side of the structure (this means six steps in total) :

1) Divide the desired position by the appropriate resolution ($\frac{x_d}{\delta_x}$ or $\frac{y_d}{\delta_y}$)
2) Define the nearest integer
3) Convert it to its binary form

Each bit of the binary number obtained represents the state of the bistable module of one side of the structure (the left side for x_d and the right side for y_d). The modules are ordered from top to bottom. The most significant bit represents the state of the top module, and the least significant bit represents the state of the bottom module.

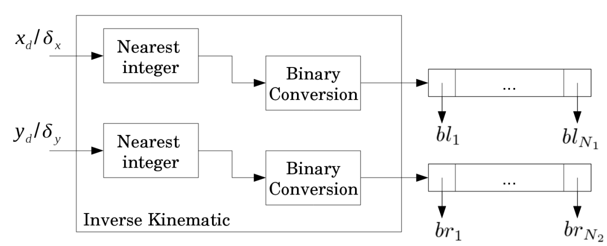

Fig. 5. Representation of the inverse kinematic calculation process

This inverse kinematics representation is only valid for the particular workspace obtained here. If we change some geometric parameters of the structure, for example changing the ratio between all the beams of the structure, this will generate a new form of the workspace. And we will have to establish a different representation.

The limitation of this representation can be observed when increasing the number of modules used. When the resolution of the workspace becomes close to 10 nm, the inverse kinematics becomes less accurate because of non linearities not taken into account.

IV. FEA SIMULATION

This digital microrobot is entirely microfabricated and build in a monolithic structure. The use of flexure hinges instead of traditional rotoid articulations prevent us from backlash and other drawbacks frequently encountered with these traditional articulations. These flexure hinges have to be characterized in order to provide good behaviors, as well as some other parameters of the robotic structure. For this, we use the results generated by the simulations made with the FEA software Ansys. All these results provide informations

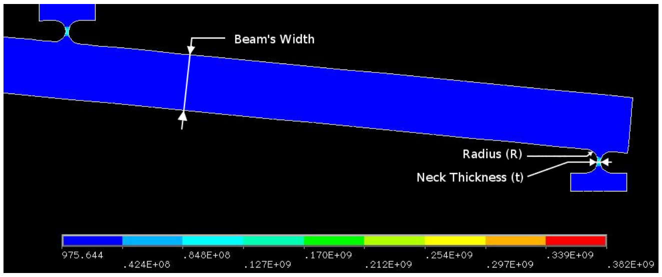

Fig. 6. Elements of the structure studied with the results of the FEA software Ansys

that can be used to choose the size of the different parts of the structure.

The bistable module was already designed in a previous study in which its dimensions were defined. We only have to take the robotic structure into account. It is composed of two different elements which are combined together several times. These elements are the pseudo-rigid beams and the flexure hinges. The properties we will focus on to choose the size of these different elements are the mechanical stress generated inside the structure by its deformation, and the force applied by the structure onto the bistable modules. While undergoing the displacement of the bistable modules, the robotic structure will deform and tend to return to its rest position as all flexible structure would do. A restoring force is then applied by the structure onto the bistable modules. This force should not exceed a certain threshold which is the blocking force of the stop blocks ($1.54\ mN$), otherwise the robot will not be robust anymore. The stress registered inside the structure should also not exceed a certain threshold which is the silicon's rupture stress. We consider here that the limit is $1\ GPa$.

A. *Hinges' Dimensions*

We will first study the case on which the structure does not undergo any disturbances. First of all we have to choose the shape of the flexure hinges we are going to use.

Three main sort of flexure hinges can be used : circular hinges, beam hinges and ellipse profile hinges. As circular hinges' deformation is located in a very small area, which can be considered as a fixed point in some cases, we will measure very high stress. On the contrary, beam hinges' deformation is distributed along all the length of the beam, generating very low stress. Finally ellipse profile hinges can be considered as a mix of the previous two kind of hinges. It provides low stress with a more located deformation area than the beam hinges. We choose here to use circular flexure hinges in order to mimic the behavior of a traditional rotoid articulation. This kind of flexure hinges will undergo high stress, but as the displacements of all the elements of the structure are very small (several microns), the stress will be acceptable. These circular flexure hinges will furthermore provide very accurate rotations with an approximately fixed instant center of rotation. A circular flexure hinge is generally defined by two dimensions : its radius R and its neck thickness t. The ration t/R is often considered because it defines the behavior of the hinge. Studies were made in [12] to define the appropriate equation to use for different wide ranges or t/R ratio. In our case, we made finite element simulation of the whole structure (without the bistable modules) to define the appropriate dimensions of the different parts of the robotic structure. We noticed that the behavior of the robot becomes acceptable with a ratio $t/R \leq 0.5$. So it seems to be a good idea to reduce the neck thickness of the hinges.

As we are going to microfabricate this robot in a clean room, it is better not to choose too small structures because errors of 1 or 2 μm can appear during the etching process and rupture risk is permanent while manipulating the structure during microfabrication. We then choose a neck thickness for hinges of $15\ \mu m$.

The curves representing the force applied on every module and representing the stress inside the structure for different values of the hinges' radius can be considered as a negative exponential curve that starts being constant with a radius of $60\ \mu m$. This radius is sufficiently high for performing small stress and forces, and sufficiently small for providing the behavior of a rotoid articulation, with the generation of a fixed instant center of rotation.

B. *Beams' width*

For this part, we consider a perturbation force applied on the end effector of the structure. We will indeed choose a structure that permits a robust workspace, which means that all the positions of the workspace should be robust to an external force. The bistable modules were actually designed in order to create robust microrobot, being able to handle forces of $1.54\ mN$. The forces generally encountered in the domain of micromanipulation are between $1\ mN$ and $10\ mN$.

We still use the FEA software to define the properties of the structure. The forces applied on every modules and the stress inside the structure were measured for all the positions reachable by the robot while it undergoes an external force from 0 to $10\ mN$. The consequence of this force is a small displacement of the whole workspace. The displacement of the workspace depends linearly on the the force applied on the end effector of the robot. For the design of the robot we are focusing on, i.e. a beam width of $300\ \mu m$ and hinges of $15\ \mu m$ neck and $60\ \mu m$ radius, a force of $5\ mN$ induces a workspace displacement of $0.5\ \mu m$. But this displacement can easily be reduced by increasing the beam's width. For instance this displacement becomes almost ten times smaller with a beam's width of $700\ \mu m$.

But the most constraining characteristic is the force applied on every bistable modules. This force should never exceed the limit of $1.54\ mN$. If we consider a structure with beams of $300\ \mu m$ width, the structure can undergo an external force of $6.5\ mN$ before reaching this blocking force on one of the six bistable modules, while with beams of $700\ \mu m$ the external force can not exceed $5.5\ mN$. As the first prototype of the digital microrobot will undergo testing of the force it can bear, we choose to use the structure that

TABLE I
COMPARISON BETWEEN SIMULATION RESULTS AND MODEL'S CALCULATION

	beam's width	
	$300\ \mu m$	$700\ \mu m$
Simulations' Resolution	$504\ nm$	$567\ nm$
Model's Resolution	$506\ nm$	$567\ nm$
Gap between the two workspaces	$43.6 \pm 3.8\ nm$	$24.0 \pm 2.2\ nm$

can handle the strongest external force, i.e. with beam width of $300\ \mu m$. Knowing the force applied on the structure, we can also imagine a control strategy which takes the displacement of the whole workspace into account.

The complete structure will then be composed of beams of $300\ \mu m$ width and circular flexure hinges of $15\ \mu m$ neck thickness and $60\ \mu m$ radius. This structure may not be the most efficient one, but it is the best to create a first prototype that will endure several tests.

C. Validation of the Forward Kinematics

The simulations made with the FEA software can also be used for a first validation of the forward geometric model we have established before. We compare the workspace generated by the simulation with the one calculated by the geometric model. The results are shown in TABLE I, in which we focused on the differences between a structure containing beams of $300\ \mu m$ width and a structure with $700\ \mu m$ width beams. The gap between the workspace generated by the simulation and the one generated by the calculation depends on the position considered. The average of the gap is $43.6\ nm$ in the case $300\ \mu m$ beam's width, and $24.0\ nm$ for a structures with beams of $700\ \mu m$ width. This offset difference is due to the deformation of the beams which is not taken into account by the geometric model. As the $700\ \mu m$ width beam will show less deformation, it is predictable that the model fits better the simulation. If we try to introduce this offset's average inside the model's equations, then the difference between the simulation and the calculation is only composed of a very small fluctuation. This fluctuation is $\pm 3.8\ nm$ in the first case, and $\pm 2.2\ nm$ for the second, which is negligible compared to the resolution of the workspace. But as we will increase the number of modules in the structure, the resolution of the workspace will decrease and the gap between the simulated positions and the calculated positions will not be negligible anymore.

The geometric model we have established before is then compatible with the simulation results. This modeling is simple (matrix multiplication), and it fits very well the behavior of the structure.

V. CONCLUSIONS AND FUTURE WORKS

In this paper we have proposed a new concept of carrying microrobot. This domain of robotic is sparsely studied, but is becoming more and more required. This digital microrobot is based on the use of bistable modules, developed in a previous study ([11]). The robotic structure has been designed to obtain a square workspace, with a high resolution. The resolution of the architecture proposed here (with 6 bistable modules) is $500\ \mu m$, but we can easily reduce it twice, four times, or even more. Each position of the discrete workspace is moreover stable and robust without the need of any feedback. This new digital microrobot offers several advantages that overcome the problems of traditional microrobots (wear, backlash, non linearity, ...). We have moreover developed forward and inverse kinematic models which are easy to manipulate and fit very well the results of the FEA analysis.

We are now microfabricating in clean room the first prototype of this microrobot, and will compare the simulation results with the real system. After that a motion planning strategy will be developed for this particular non-redundant workspace.

VI. ACKNOWLEDGMENTS

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