Study and implementation of electrostatic actuation for programmable matter modules

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Abstract— **Actuation of micro-robots in relation to the field of programmable matter has been the aim of most researches working on the topic. Most studies have concentrated on the ability of these robot modules to latch with one another and to be able to move around each other to form the desired configuration. These mostly have been based on Modular Self re-configurable Robots (MSR) which use mechanical, magnetic or pneumatic method in their manoeuvres. However, these have been faced by the challenges of miniaturization, power consumption and power transfer between modules. Electrostatic actuation has attracted more interest in recent works due to the ability to scale down the modules and to use the configuration for power transfer and communication. In this work, we propose to use electrostatic chuck principle to actuate modules having a cylinder form. Instead of using one array of electrodes, two columns of electrodes array, positive and negative, are considered to increase the force generated by the chuck effect. An array of electrodes prototype has been fabricated using lithography process for validating the actuation. A sufficient force and torque are generated for latching and making the cylinder rolling respectively, thus validating and showing the potential of electrostatic actuation for miniaturized programmable matter application.**

I. INTRODUCTION

Programmable matter concept refers to a matter that can self change its shape, optical properties, color, conductivity, density and so on. This concept was introduced by Toffoli and Margolus in the late 1980s. In their referent paper [1], they reported different concepts of programmable matter and they defined the necessary requirement for its design. Following this work, several studies were carried out to proof the viability of the implementation of programmable matter from physical point of view. Most of them are based on modular robotics approach where the module is broken down to basic functionalities such as latching, locomotion and communication.

Modular robotics is a field that offers flexibility and robustness in the general application of robotic systems in day-to-day life. It is reproducible and cost effective[2] when it comes to mass production of single modules which are combined to form a Modular Robotic System(MRS). Ahmadzadeh and Masehian [3] define a modular robot as an array of kinematically-constrained simple robots with few degrees of freedom that attach to or detach from each other and form a modular structure or a configuration. These configurations enable the robot to be used in different applications due to their ability to change their physical pattern to suite a desired application[4]. The modules have active and passive connectors that facilitate their attachment and detachment when changing their configuration in addition to the basic components of the convectional robots. When a MRS is capable of deciding on its own the best suitable shape or form to perform a given task, to be able to detect, discard and replace faulty modules within the robot, it is termed Modular self- reconfigurable Robot (MSR)[2], [5].

The first MRS was developed in 1985 in the Science University of Tokyo by Fukuda and Ueyama[3]. The developed modules of the robot were termed *cells* and thus the name CEBOT which is an abbreviation for cellular robotic system[6]. The cells would achieve the dynamic reconfiguration by co-ordinated random walks to search for compatible modules in an environment of many cells through the use of a software. Inspired from this work, many prototypes have been created in order to test the feasibility of MSR for different applications as shown in the literature [2], [5], [3], [7], [4].

It is obvious from the literature that more keen interests have been put to the latching methods that enable the modules to form an ensemble and maintain the desired configuration. Mechanical latching has been used in different modules such as Atron [8] and SuperBOT [9]. Other modules use magnetic forces like M-Tran[10] developed by Murata et al. and the magnetic planar module developed by Kirby et al.[11]. These modules provide high latching forces and are able to move with respect to one another. There are also few modules that use pneumatic system for the latching. Garcia et al.[12] designed a vacuum based adhesive for holding modules together while forming the ensemble. In 2015, Romanishin et al.[13] developed the most advanced modules called 3D M-block which has demonstrated capability of independent functionality. These modules use inertial actuators to provide controlled torque in order to create pivoting motions about the three axis. Additionally, they are able to move relative to one another and form a desired structure. The modules use magnetic forces to couple with one another to maintain the structure. The design has minimized the number of actuated parts and the complexity of their form thus simplifying the manufacturing process. Having internal power supply and the possibility to

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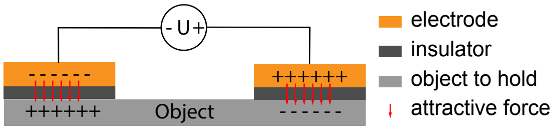

Fig. 1. Electrostatic chuck principle

control each module independently is a desired feature in the application for programmable matter. However, the question of power transfer and miniaturization remains a challenge due to its hybrid design.

Electrostatic actuation offers a promising solution when it comes to these challenges especially miniaturization. The scaling effect for electrostatic charges is favorable and viable for the latching and actuation of modules since as the units are scaled down, the electrostatic forces grow relative to the required forces for the modules [14][15]. Another benefit related to electrostatics is the energy efficiency of the modules. In a leakage free environment, when charges are supplied to a module, they remain indefinitely thus making it possible to maintain the modules in position for a long time even if the supply is disconnected.

In the context of claytronics project, Karagozler et al [16] described in 2009 how by using electrostatics actuation, it is possible to create mass producible sub millimeter Catoms fulfilling the *ensemble principle*. The principle states that: A unit should include only enough functionality to contribute to the functionality of the ensemble [16]. This was the first time analysis based on electrostatics was done in relation to programmable matter. Proof of concept models were created but more analysis on the distribution of electrodes for optimum torque and force generation, for actuation and latching respectively, is lacking for the proposed module. In addition, experimental validation is lacking. In this work, we propose to use electrostatic actuation in particular the chuck principle to actuate module having a cylinder form. Here, we propose a new electrode's distribution that increases the generated force and torque. Instead of using one array of electrodes, two columns of electrodes array, positive and negative, are considered here. FEA analysis were carried out to demonstrate the efficiency of this new distribution according to the ones proposed in [16]. Then, a prototype array of electrodes was designed and fabricated using lithography process for validating the actuation. Sufficient force and torque were generated for latching and making the cylinder rolling respectively, thus validating and showing the potential of electrostatic actuation for programmable matter application.

II. DESIGN, MODELING AND ANALYSIS OF A CYLINDER MODULE

Electrostatic phenomena have been known for several centuries and its use for the design of electrostatic actuators is clearly evident. These actuators are based on Coulomb's law between two electrically charged bodies, which creates mechanical work and subsequently movement controlled by the potential difference between the two bodies. Basic electrostatic actuators consist of two planar electrodes subjected to a potential difference. As a simple actuator it is easy to implement, however it requires to use the same power source to supply two different modules. To overcome this limitation and take advantage of electrostatic actuators chuck effect is privileged in programmable matter field because each module can be self powered by a battery or an external power source.

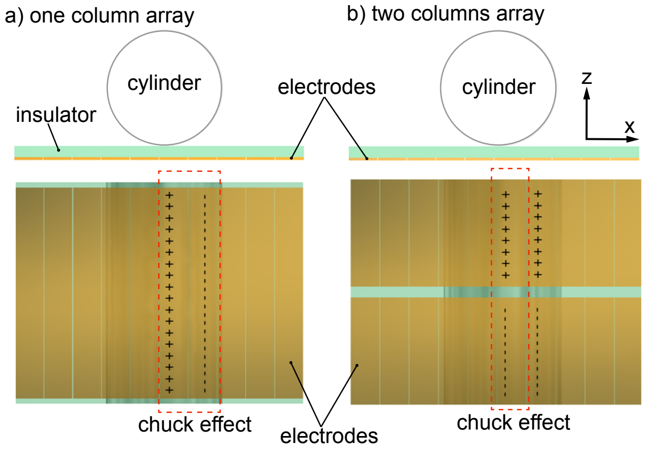

Fig. 2. Electrodes array configurations. a) one column electrodes array distribution, b) two columns electrodes array distribution.

A. Electrostatic chuck effect

When electrodes with opposite polarity are covered by a small layer of insulator and a conducting object is placed on the surface, an attractive force is created between the two bodies as illustrated in Fig. 1. This summarizes the main principle of the electrostatic chuck effect. Using the same principle as classical electrostatic actuator, the force calculation based on virtual work remain similar for this effect.

B. Electrodes distribution

For simplicity, the demonstration of electrostatic chuck effect is done by assuming a cylinder that latches and rolls on a plan with distributed electrodes. Figure 2.a shows the distribution proposed in [16]. The choice made in this study consists to distribute electrodes along one axis by alternating positive and negative electrodes. As a direct consequence, at least two successive electrodes are needed to generate the chuck effect. In this case, the first electrode is close to the contact point of the cylinder while the second is a little bit far from the contact point. According to the mathematical model reported in [16], the generated force by the second electrode is low since it strongly depends on the gap between the electrode and the cylinder. Although, the generated force could be enough, it clearly appears that there is room for improvement especially in regard to the electrodes distribution. In this view, we propose in this work to distribute electrodes along x and y axis as shown in Fig. 2.b. The idea consists to maximize the chuck effect by placing positive and negative electrodes as much close

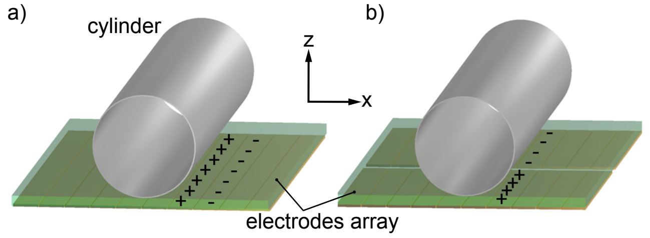

Fig. 3. FEM models. a) one column electrodes array distribution, b) two columns electrodes array distribution.

as possible to the contact point of the cylinder. Instead of using one array of electrodes, two columns of electrodes array, positive and negative, are considered to generate chuck effect. As can be seen from Fig 2.b, this configuration allows to distribute on the cylinder side one position electrode and one negative electrode. With a minimal distance between the electrodes and the cylinder, the generated force would be much higher than the above mentioned distribution. This will be demonstrated in the next subsection where FEA analysis are carried out.

C. Simulation

1) FEA analysis: To evaluate the generated force and torque, FEA simulations are conducted on both distributions: one array distribution and two columns array distribution. Figure. 3, illustrate both of them where several parameters are taken the same to make easy the comparison: same wafer, same insulator material and thickness, same gap between electrodes, same width of electrodes and same conductive material for electrodes. The only difference relies on the electrodes length and their placement. All the parameters are summarized in Tab. I. In the first distribution, each electrode covers all the side of the cylinder and two successive electrodes are needed to generate chuck effect. Whilst, in the second distribution, the electrode along the cylinder side is split on two electrodes that can be used to generated the chuck effect. For each configurations, a FEM model is built under ANSYS electronics software and several simulations are carried out to analyze the influence of electrodes on the generated force and torque.

2) Results: Table II summarizes the obtained results for an excitation voltage of ±100V. For each distribution, simulations are conducted for three different diameters of the cylinder (1 mm, 2 mm and 5 mm). During the simulations, the force along z axis and the torque around y axis are evaluated. In the first configuration, two successive electrodes are activated as shown in Fig. 3.a. Whilst, in the second configuration one pair of electrodes is activated as shown in Fig. 3.b.

TABLE I
SUMMARY OF THE FEM MODEL PARAMETERS.

Parameter	Value
Insulator material	SiO2 (dielectric constant 10 V/cm)
Insulator thickness	200 μm
cylinder diameter	1 mm, 2 mm and 5 mm
cylinder material	Aluminium with 25 μm thick
cylinder length	8.4 mm
Electrode material	perfect conductor (gold)
Electrode gap	10 μm
Electrode thickness	50 μm
Electrode width	500 μm
Electrode length for long electrodes	8 mm
Electrode length for short electrodes	4 mm

TABLE II
SUMMARY OF THE FEA ANALYSIS RESULTS.

	One column array configuration	
	Force (N)	Torque (N.m)
cylinder with 1 mm diameter	-1.41e-8	-1.7831e-12
cylinder with 2 mm diameter	-4.2018e-9	-1.2498e-11
cylinder with 5 mm diameter	-2.61e-8	-1.0177e-11
	Two columns array configuration	
	Force (N)	Torque (N.m)
cylinder with 1 mm diameter	-1.2393e-5	-4.6724e-10
cylinder with 2 mm diameter	-1.2509e-5	-5.1803e-9
cylinder with 5 mm diameter	-1.1966e-5	-1.2099e-10

As expected from the mathematical model of the electrostatic force, the results show clearly that one column array distribution generates a low amount of force and torque. This is mainly due the electrodes distribution where the second electrodes is a little bit far from the contact point. As a direct consequence, the generated force is low since the gap between the electrode and the cylinder is a little bit higher in comparison with the first electrode. For instance, in the case of 1 mm cylinder diameter one column array generates a

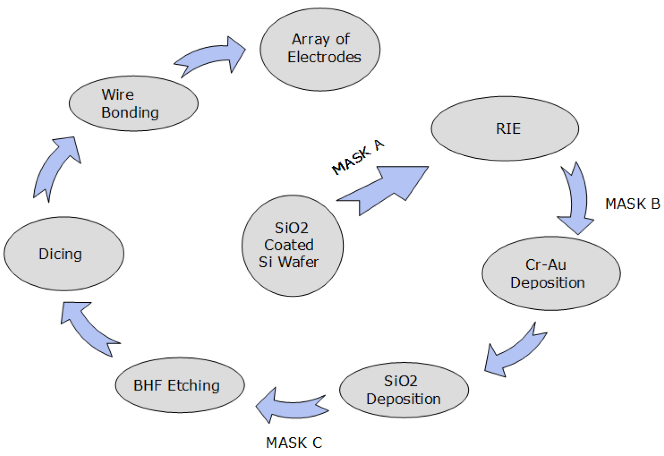

Fig. 4. Process flow diagram.

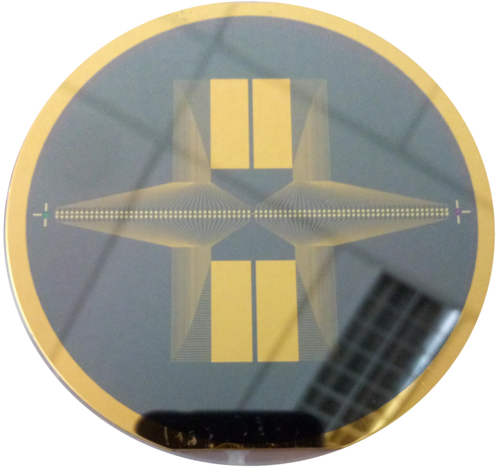

Fig. 5. electrode's array prototype.

force of -1.41e-8 N, while the two column array generates a force ∼800 times higher, i.e, -1.2509e-5 N. In the other hand, the first column array generates a torque of -1.7831e-12 N.m, while the two columns array generates ∼260 times higher, i.e, -4.6724e-10 N.m. Obviously, this also applies to the rest of the results. It is worth to notice that the torque values are not proportional to the force in both cases because the area covered by the electrodes in both configurations is different. Therefore, the application point of the force is different for both configurations.

In summary, the result analysis reveals that the two columns electrodes distribution generates much higher force and torque than one column distribution. This validates the above-mentioned hypothesis. To confirm experimentally these results, a prototype is designed and fabricated as described in the next section.

III. MODULES AND ARRAY OF ELECTRODES REALIZATION

To guarantee a quasi perfect flatness of the planar electrodes, we privileged clean room fabrication techniques. The whole process starts from a silicon wafer followed by electrode and insulator deposition. In parallel, a very light cylinder modules are made by rolling a thin sheet of aluminum around a cylinder having a diameter of 2 mm and 3 mm.

A. Cylinder module realization

Referring to [14], the total force generated by a pair of electrodes must be able to overcome the weight of the module in order to roll the module. In addition to the electrostatic force, it is clear that the weight of the module plays an important role to achieve this rolling movement. To make this weight as much smaller as possible, we fabricated cylinders by using very thin aluminum sheet. The process starts by cutting a small rectangular sheet that corresponds to the unfolded cylinder. Then, the small sheet is folded by rolling it around a cylindrical pattern. By repeating the process, several cylindrical modules with different diameters can be fabricated.

B. Electrodes array realization

The electrode array is fabricated as a monolithic bloc using single-crystalline silicon-on-insulator (SOI) wafer with a layer of SiO_2. To ensure the flatness of the electrodes, a clean room fabrication techniques are used. As illustrated in Fig 4, the clean room process used revolves around six major steps including three different masks:

1- Partial trench openings (300nm/1200nm) by DRIE/RIE for buried electrodes on Silicon wafer
2- Cr-AU Electrodes deposition by sputtering and Lift off
3- Insulation of Front side of the full wafer with SiO2 by Chemical Vapor Deposition
4- Connection opening by BHF etching
5- Dicing of the wafer
6- Connecting the electrodes to PCB through Wire Bonding

During the realization, various challenges involving the lift off process and photolithography processes were faced. This involved the lifting off of the desired parts of the Gold deposition and short circuit. The fault was solved by cleaning the wafer and modifying the parameters during the baking and the spinning of the photoresist. Whilst, the correction of the short circuit was done by Focused Ion Beam (FIB) etching on the surface of the wafer to separate the electrodes. Achieving all these steps leads to the electrodes array prototype shown in Fig. 5. Finally, the array prototype is connected to electronic circuit equipped with Arduino controller. This circuit allows to program sequences that turn-on or turn-off the electrodes.

IV. EXPERIMENTAL VALIDATION

A. Experimental bench

The experimental bench was set in order to assess the ability of the electrostatic chuck effect and the actuation of a cylindrical module. As depicted in Fig. 6, it comprises a power supply, an amplifier, an array of electrodes, cylindrical modules, an electronic and switching circuit connected to a laptop computer. The amplifier makes it possible to have a

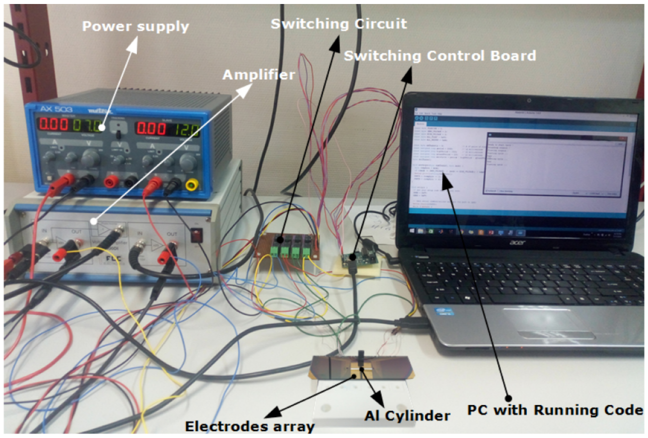

Fig. 6. Experimental bench.

negative and positive polarity on the supplied voltage due to its dual polarity output. The cylindrical module is rolled from a thin aluminum foil using a smooth glass template with different diameters. The electrical switching circuit was made by using relays. This circuit enables the switching of electrodes by first grounding all the electrodes to discharge them. A high signal is sent to the pair which turns the outputs of the relays to the desired voltage for a given time. The circuit is switched to ground to eliminate residual charges on the dielectric and the plates for a specified time and there after a waiting period is given before switching to the next pair of electrodes. The switching was made possible by the use of Arduino control board whose outputs were used to send the commands to the switching circuit. The switching sequence required to latch or to roll the module is realized by coding the Arduino circuit where the rest of the circuit parameters are kept constant.

B. Tests and results

Before testing the latching and the rolling of the module, several tests were made to determine the breakage voltage between the electrodes and the module. For this purpose, a series of voltage going from ±100 V to ±160 V were applied to test the maximum voltage that can be supplied on the electrodes pair without reaching the dielectric breakdown. According to the observation on the set-up, the maximum voltage was found to be ±140 V. Keeping in mind this voltage as a limit, static and dynamic tests were conducted to demonstrate the latching and the rolling of the module.

1) Static test - latching: To test the latching capabilities, first a cylinder module with a diameter of 3 mm is placed on the electrode array. Then, the closest electrodes pair is supplied by ± 140 V. As shown in Fig. 7, a force is generated to latch the module on the array electrode. For further demonstration, the electrode array is tilted progressively till 180 Deg. As can be seen from the screen-shoots (a,b,c,d,e and f), the module remains always latched to the electrodes. Thus, the electrodes pair generates a sufficient amount of force that allows to latch the module even for the critical case where the electrodes array is tilted by 180 Deg.

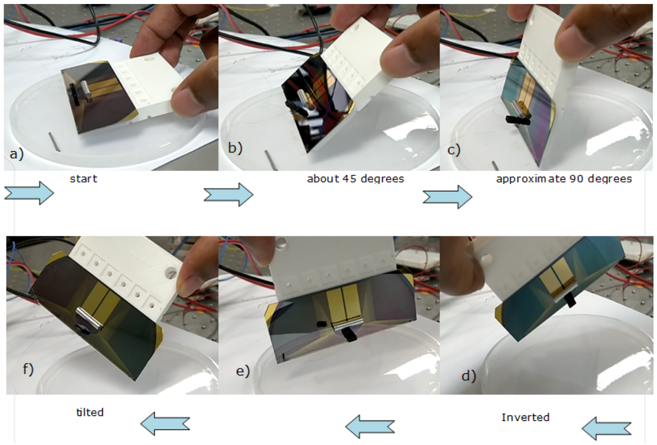

Fig. 7. Latching test of a module. a) start position (planar), b) tilt of 45 Deg, c) tilt of 90 Deg, d) inverted electrode array (tilt of 180 Deg), e) and f) return to the start position while tilting the array.

2) Dynamic test - rolling: The dynamic test aims to demonstrate the capability of the electrostatic actuation to roll a cylinder module along the electrodes array. The idea consists to actuate successively several pair of electrodes which creates a force that propagates from one pair to another. And in turn, the module can roll when subjected to this force. For this test, a cylinder with a diameter of 2 mm is used and an actuation sequence of electrodes pair is programmed. As illustrated in Fig. 8, the module rolls easily on the electrodes array when the actuation sequence is activated. Starting from a given position, the module moves each time the adjacent electrodes pair is activated and the previous one is deactivated. The sequence is repeated three times which allows to the module to move from position a to position d passing through positions b and c. Thus, the electrodes pair generates a sufficient amount of torque that makes rolling the module.

V. DISCUSSION

From the static test it is obvious that it is possible to latch and maintain the contact of the cylinder on the electrodes pair. The generated force is largely sufficient to hold the cylinder for all the tilted angles as shown on Fig. 6. The array of electrodes is turned upside down and the cylinder is still stuck on the electrodes array. In the other hand, the dynamic test shows the possibility of changing the location of the cylinder by applying a voltage on the pair of electrodes which are adjacent to the equilibrium contact point of the cylinder as discussed in Sub-Sec. II-B. This creates an attractive force on the cylinder and makes it move to the direction of the programmed motion sequence as shown in Fig. 8.

It is worth to notice that it is possible to guarantee the latching and the rolling for a lower voltage. This aspect is out of the scope of the study since our main objective is to prove the electrostatic actuation capabilities while keeping in mind only the breakdown voltage limit. This is why here a supply voltage of ±140 V is used for static and dynamic tests.

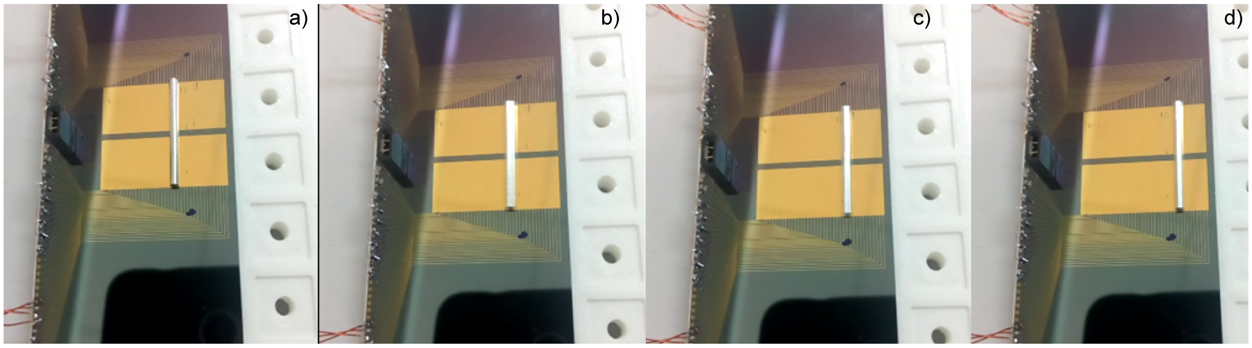

Fig. 8. Rolling test. a) start position, b) and c) intermediate positions, d) target position.

VI. CONCLUSION

In this paper, the electrostatic chuck effect is studied and implemented for programmable matter application. For simplicity, a cylindrical module latching and rolling on a plan with distributed electrodes is considered. Unlike the previous works where positive and negative electrodes are distributed along one axis, this study comes with new electrodes distribution where the electrodes are placed as much close as possible to the contact point of the module. Instead of using one array of electrodes, two columns of electrodes array, positive and negative, are considered to generate chuck effect. Starting from the electrodes sketch, two FEM models are derived (one column electrodes and two column electrodes). Then, the force and torque generated by each configuration are evaluated through FEA analysis. The obtained results show clearly the superiority of the two columns array configuration to generate much force and torque in comparison with one column configuration. To validate experimentally this configuration, a prototype of two column electrodes array is fabricated using clean room process and cylindrical modules are fabricated by folding aluminum sheets. Several tests are conducted to (i) determine the breakdown voltage, (ii) evaluate the latching capabilities and (iii) evaluate the rolling ability of the module. Preliminary results show a good agreement and confirm the FEA analysis expectations. In one hand, the latching principle is demonstrated by holding the cylinder on the electrodes plan even for a tilt of 180 Deg. In the other hand, the rolling principle is demonstrated through a dynamic test where the module moves form a position to another under the effect of the attractive force generated by the successive pair of electrodes. Although, the generated force and torques are enough, it clearly appears that there is room for improvement especially in regard to the level of the applied voltage and the position control of the module within the plan.

Future work will focus on the position control of the cylindrical module by generating specific sequences or by using visual feedback. The work would also investigate the validity of the electrostatic actuation in the case of spherical module.

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