First evaluation of a system of positioning of Microrobots with ultra-dense distribution.

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***Abstract*— Microrobots applications evolve in ultra-dense contexts. They are at the stage of the simulation to obtain 2-Dimension or 3-Dimension shapes for the deployment of individual or collective intelligent programs. In this work we address the individual positioning of MEMS micro-systems and components. In many situations, it is more useful to have a local information on the relative positions of Microrobots and their orientation, than an absolute position of each robot.**

Works on microrobots micropositioning are either stochastic and are based on probabilistic approaches, that give better results on a small scale, but produce greater error accumulation with a large sample ; or deterministic and based on geometric considerations to accurately calculate the position of each item, and then distribute it to the other microrobots.

We propose a model of a smart-grid (orthogonal and hexagonal lattice) of microrobots with regular geometry, and their connectors (actuators and sensors for moves and other actions) communicating by contact. Based on this model, we propose an algorithm of mixed positioning (absolute and relative) in 2-Dimension and 3-Dimension without mobility of microrobots in a set ranging in size from thousands to millions of items, based only on the relations of neighborhood. Then by simulation we perform a functional validation of our algorithm, the next stage will be a validation of the scalability of our algorithm on orthogonal grid of over 1 million Mems.

I. Introduction

The miniaturization of the automated systems continues inexorably. With her, the densification of the systems reaches the million items in one m^3, requiring new strategies of coordination. In such systems, communications aspects between Mems, the individual and collective positionings of Mems, and finally the modelling of these systems constitute so many challenges in the academic and industrial communities.
Microrobots endowed with these ways are still at the stage of the design. The current microrobots however communicate by contact and in real time when the classic robots communicate without contact but for very low densities (of the order of 2 to 6 robots by room). Microrobots are used in various applications, as for the construction of intelligent 2D / 3D forms (programmable matter - claytronics[4]), or still within the framework of miniaturized flexible workshops where elements collectively realize actions. All these applications require a precise knowledge of the position of the microrobots. In many cases, it is more useful to have a local information about the relative positions of microrobots and their orientation, than a global position of every robot.

The Mems, because of their small size, cheap price and the fact that they are mass produced, millions of units can be used in very small spaces. The Distributed intlligents MEMS [2] systems consist of a large number of MEMS, capable of fulfilling advanced tasks (forms construction), result of the addition of elementary actions of each of its constituent.
Distributed Mems systems can be classified into two categories according to their topology : static or dynamic. Static distributed Mems have a fixed physical topology that will not change over time, while dynamic are composed of mobile units, making them dynamic logical topology.

A. Summary of our contributions of modeling algorithm and validation

In the remainder of this paper, we propose at first a model of a microrobots smart-grid (orthogonal and hexagonal lattice) with regular or irregular geometry, and of their connectors (actuators and sensors for displacements and other actions) communicating through contact. Secondly, starting from this model, we propose a mixed positioning algorithm (absolute and relative) in 2D and 3D without mobility of nodes in a group ranging in size from thousands to million of items, based on neighborly relations depending on exchange links between micro-robots. Thirdly, we perform a functional validation of our algorithm. Fourthly we analyze the results and present prospects for this work.

II. State of art

Works on microrobots positioning [5], [10] , [8], [3], [11] are exclusively academic. They are structured from state projects or communities of states. The nature of these works are still something of simulation and scaling faces on one hand the number of microrobots that have to communicate and cooperate, and on the other hand, a quite relative functional and geometrical simplicity. The maximum size of the robots grid does not exceed 10000 robots. In other works which cover the simulation of application of systems reconfiguration, the number may reach 400000 [1], but the calculation of positioning is collective (in groups of 3 catoms). It is handled in an implicit way applied in the context of a virtual territory discovery. It is the simulation of the Nano-wireless communications which is the first target

of this work.
This works show that the size of MEMS or microrobots elements considered range from a few dm^3 to a few mm^3, that communication technologies are moving towards a wireless infrared communication (whereas previously the preferred communications technology between the robots were a matter of Bluetooth or WiFi). This works also reveal that the techniques of positioning are either probabilistic [10], [3], or exact [8], [11], by neglecting the inherent uncertainties in the transmission of signal either still in the errors of mechanical or physical adjustments errors when switching to experiment with real prototypes. More important for our choices of orientations of works, positioning types are never mixed, that is to say, combining absolute positioning and the relative. Furthermore, the communication by contact is not understood in academia, the responsiveness of the positioning calculation is not measured in these dense systems of microrobots.

III. Mems System

A. Related concepts

A MEMS is a micro-electromechanical system comprising one or more mechanical components using electricity as energy source in order to perform a function of sensor and/or actuator, with at least one structure having micrometric dimensions. A connector is a sensor/actuator enabling MEMS to dock with each other. These connectors are also used for communication by contact, the energy transfer, solidification and dislocation of the material, and the movement of Mems. Communication allows MEMS to exchange messages, information, and ensure overall coordination of the MEMS system. Several types of communication exist for Microrobots. According to the used medium, we find the wired, molecular, acoustic, electromagnetic, or contact communications. Mems studied here, communicates by contact of neighbor with neighbor. They have connectors that are actuators also used for communication. Physically, a MEMS can have a shape more or less regular. We find Mems with cubic, cylindrical, or spherical form. In this work, we consider regular or irregular shapes Mems, with on their surface $\overline{C_{M_i}}$ connectors. The relative arrangement of Mems and it's neighbors allows to define a structure of regular grid. The circular geometry of Mems forces them to a maximum of 6 neighbors. When every Mems can have 6 neighbors, all the possible positions of Mems forms a hexagonal lattice. In the situation or every Mems admits the most 4 neighbors, we obtain an orthogonal grid. This structure defines then all the possible positions that Mems can occupy.

B. Modeling must take into account more heterogeneity of Mems and those of their connectors

In our previous work [9], we made a full modeling of our Mems and their connector. The figure 1 from this previous work, present a model of a 2D circular Mems. This model prensent a Mems with its center O_{M_0}, its local landmard vectors $\overrightarrow{x_0}$, $\overrightarrow{y_0}$; and its connectors $\{C_{0,j}\}_{0\leq j\leq \overline{C_M}}$. On this figure we mark as A the absolute position and as R the

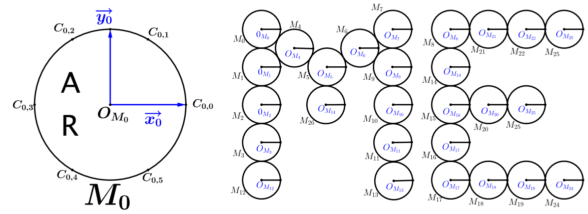

Fig. 1. Shape form by circular 2D Mems arrange in a honeycomb grid (to form M) and an orthogonal grid (to form E) and a higliht of a Mems with it's landmanks and surface connectors

relative position of the Mems.
For a Mems M_i, we model its $j-th$ connector as follows : $Connector_{i,j} = (C_{i,j}, PosR(C_{i,j}, M_i), Etat_{i,j}, Fonct_{i,j})$ In this formula, $C_{i,j}$ is the identifier of the connector j of the Mems M_i . and $PosR(Ci, j, M_i)$ is the relative position of the connector $C_{i,j}$ in the repository $\mathcal{R}_i = (O_{M_i}, \overrightarrow{x_{M_i}}, \overrightarrow{y_{M_i}})$ of the Mems M_i. $Etat_{i,j}$ the state of the connector $C_{i,j}$. A connector have a number of states that define its operation and the possible exchanges he can have with the connectors of other Mems around him. $Fonct_{i,j}$ the features of the connector $C_{i,j}$. A connector is able to perform several functions : sense, act, attract, repelling, send messages, receive messages, hang, lift, dock, undock, etc ...

We give below the modelling of Mems :
$Mems_i = (id_{M_i}, O_{M_i}, \overrightarrow{x_{M_i}}, \overrightarrow{y_{M_i}}, Geo_{M_i}, C_{M_i}, \beta_{M_i},$
$Fonct_{M_i}, Pos_{M_i}, L_{M_i}, N_{M_i})$
With :
id_{M_i} : the identifier of Mems M_i. O_{M_i} : the center of the Mems M_i. $\mathcal{R}_i = (O_{M_i}, \overrightarrow{x_{M_i}}, \overrightarrow{y_{M_i}})$: the local landmark associated with Mems M_i. It's used to define an orientation associated with this Mems. We assume that the landmarks of all Mems have the same orientation. Geo_{M_i} : $Mems_i$ geometry. What is included in the geometry of the MEMS is the position of its center, as well as the relative positions of the connectors relative to its center in the local landmark associated to the Mems. C_{M_i} the set of the of Mems M_i connectors. $\beta_{M_i} = (\widehat{\vec{x_{M_i}}, \overrightarrow{O_{M_i}C_{i,0}}})$ is the orientation angle of Mems M_i $Fonct_{M_i}$ the features of the Mems M_i. The MEMS has several features : communicate, move, run, load/unload, store.

Pos_{M_i} the position of Mems M_i. Each Mems has an absolute position and a relative position. The absolute position is the position of its center in a common reference to all of our Mems system. We note it $PosA_{M_i}$.

L_{M_i} the set of Mems M_i links, and N_{M_i} the set of the nearby Mems of Mems M_i.

IV. Micro-robot Positioning Algorithm

We propose here an algorithm of positioning within our system of Mems. It uses the communication by contact between Mems and cooperation between nearby Mems to spread information being used to the calculation of positions. It allows when in a related component, there is Mems having an absolute position to calculate an absolute position for the set of Mems of this related component ; and when there is not at least one Mems having an absolute position, to lean on Mems having a relative position, or just on the relation of neighborhood and the cooperation to define the relative positions of Mems. Our positioning system works in the following way :

1) **Initialization : choice of references Mems.**
   In a first stage, we choose Mems of reference. If the list of Mems with a known absolute position is not empty, we choose Mems in this list as Mems of reference. If this list is empty, we choose Mems of the lowest number as Mems of reference.
2) **Construction of the neighborhood of reference Mems**.
   The following stage consists in building the neighborhood of Mems of reference. Each Mems possesses physical neighbors who are in physical contact with him ; and connections which are communication channels between him and nearby Mems physically through their connectors. Thanks to its connectors and to their state, Mems knows if it has a connection or not. Thanks to the connections established with nearby Mems physically, Mems builds its table of neighborhood. The table of neighborhood of given Mems is so constituted by all the Mems which are neighbors to it physically, and in contact with at least one of its connectors through one of their connectors.
3) **Calculation of the position of Mems of the neighborhood** For every element of neighborhood we are going to calculate its relative position. The difficulty of this calculation lives on the fact that there is no global mark shared by all. Every mark of every Mems M_i being made of an origin situated in the center of Mems and made of vectors $\vec{x_i}$, $\vec{y_i}$. In this mark, every connector has a relative position. We formulated hypotheses of simplification which allow us to calculate the relative position. Resting on the hypothesis of contact and considering that two connectors in contact occupy the same position. The calculation of the relative position is made as follows :
   a) $PosR_{M_i,M_k} = (\overrightarrow{O_{M_i}O_{M_k}})_{\mathcal{R}_i}$
      in the landmark $\mathcal{R}_i = (O_{M_i}, \overrightarrow{x_i}, \overrightarrow{y_i})$ associated with $Mems_i$
   b) $(\overrightarrow{O_{M_i}O_{M_k}})_{\mathcal{R}_i} = (\overrightarrow{O_{M_i}C_{i,j}} + \overrightarrow{C_{i,j}OM_k})_{\mathcal{R}_i}$
      using Ci, j applying the Chasles relationship
   c) $(\overrightarrow{C_{i,j}OM_k})_{\mathcal{R}_i} = (\overrightarrow{C_{k,l}OM_k})_{\mathcal{R}_i} = (\overrightarrow{C_{k,l}OM_k})_{\mathcal{R}_k}$
      $\mathcal{R}_k$, the landmark associated with Mems M_k ; $C_{i,j}$ and $C_{k,l}$ being in contact we can consider them as being has the same position, thus we consider that the point $C_{i,j}$ is equal to the point $C_{k,l}$
   d) $(\overrightarrow{C_{k,l}OM_k})_{\mathcal{R}_k} = (-\overrightarrow{OM_kC_{k,l}})_{\mathcal{R}_k} = -PosR_{k,l}$
   e) $(\overrightarrow{O_{M_i}C_{i,j}})_{\mathcal{R}_k} = PosR_{i,j}$
   f) $PosR_{i,k} = PosR_{i,j} - PosR_{k,l}$
4) **Calculation return of the position of nearby Mems.**
   This is made in the same ways the stage 3. has been done.
5) **Calculation of the Mems absolute position.** The calculation of the absolute position leans on the broadcasting of information. Because of the weak resources which Mems has, our choice is the one not to use the usual techniques (dead recogning, ordometry) to calculate the absolute position. We consider that we possess within our system at least one Mems that the absolute position is known. Thanks to the previously calculated relative positions, Mems can determine its absolute position as follows : When it receives a message with the field absolute position not empty, having to determine the position relative as in (3), it uses it to calculate its absolute position as follows : $PosA_k = PosA_i + PosR(k, i)$

By correctly handling the removal of all the Mems that the absolute position have been calculated, we determine the absolute position of all Mems in the related component. Figure Fig.4 present an example of our Mems distributed system, on an orthogonal grid, with each Mems having a maximum of 4 neighbours. The initial configuration present our system at the begining, in each ralated component, we have a Mems with an absolute position. In the final configuration, each Mems now have and absolute position, wich have been calculated for those who did not previously have an absolute position.

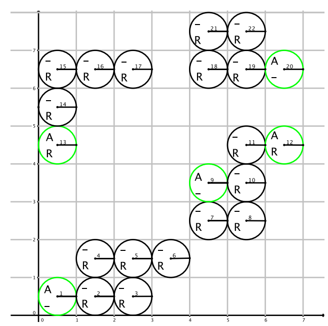

Fig. 2. Initial configuration

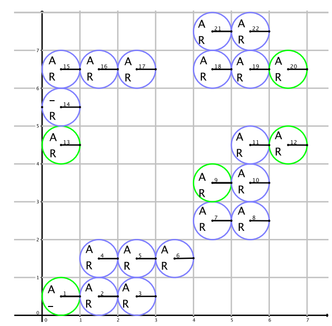

Fig. 3. Final configuration

Fig. 4. Initial an final configuration of 22 Mems distributed on an orthogonal grid, in 4 connected components, each having initially at least one Mems with and absolute position. Applying our algorithm aims to calculate the absolute position of all Mems.

V. Analyses, discussions and perspectives

In this section we present experimental results that illustrate the validation of our algorithm. We have developed Java simulations, which model 2D MEMS. Each Mems is modeled in 2D circular, With on its surface 4 connectors regularly spaced. This number of 4 connectors allows to define up to 4 physical neighbors for each Mems. When there is a connection between two nearby Mems, they can then exchange information. The communications between Mems are made by contact.

Our simulations tests are in 2D dimension. The sets are generated in a random way. Due to the circular geometric structure and the number of neighbors, we perform our tests on an orthogonal grid where each cell is a square of length

TABLE I

FUNCTIONAL VALIDATION TESTS. (INIT : INITIAL ; FIN : FINAL)

	Distribution												**Complexity**			
Test Id	Numbers of global positions		Numbers of relative positions		Numbers of global and relative positions		Numbers of positions neither global nor relative		Numbers of Mems with links inconsistent		Numbers of related components		processing time	maximum number of elements (MNE)	Actual number of elements (ANE)	occupation rate
	Init	Fin	Init	Fin	Init	Fin	Init	Fin	Init	Fin	Init	Fin	calculation time	l*c*nbmc		ANE /MNE
1	1	40	1	40	0	40	38	0	0	0	1	1	< 1 ms	64	40	0.625
2	0	0	1	0	0	0	39	0	0	0	1	1	< 1 ms	100	40	0.4
3	5	22	0	22	0	22	17	0	0	0	5	5	< 1 ms	64	22	0.34375
4	5	18	0	18	0	18	17	0	1	1	5	5	< 1 ms	64	22	0.34375

equal to the diameter of a circular MEMS, and contains at most a MEMS. In case every Mems possesses 6 neighbors, we can also have a hexagonal grid in the form of honeycomb, where every Mems is registered in a regular hexagon. All tested MEMS are homogeneous and the determined positions are in cartesian coordinates. The positioning of elements is relative and/or absolute, depending on the initial state of the system.

The tests of configuration number 1 to 3 of Table I are functional validation tests.
They validate : The successful completion of the relative or absolute positioning algorithm of a homogeneous system of Mems communicating by contact. The good realization consists of the ending and the correctness of the calculated result. Accepted configurations correspond to all combinations of relations with the immediate neighborhood for the coherent types of links with the relative positions. The calculation of relative positions between elements in contact and connected (by link). The spread of the calculation of the absolute position within a connected component. The validation of the consistency of the positions calculated with regard to links. The validation of the ending and the calculation of its convergence.

The test of configuration number 4 represents a test of the coherence of the connections by reports to the relative positions. This test has the same parameters as the test of configuration number 3 ; with the only difference of one relative position incoherence, of this fact, the number of global positions at the end the test is 18 and not 22 because of the inconsistency which limits the distribution of the global position to the other Mems.
We need to perform tests to evaluate the passage on scale of our algorithm. Unlike existing studies that position few micro-robots, our work need to go beyond [3] which positions up to 10,000 micro-robots. We intend to evaluate our algorithm on sets of Mems that can reach the million of element, with calculation time above 2 minutes (because of the needs for reactivity of our system).

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REFERENCES

[1] Nicolas Boillot, Dominique Dhoutaut, and Julien Bourgeois. Using nano-wireless communications in micro-robots applications. In *Proceedings of ACM The First Annual International Conference on Nanoscale Computing and Communication*, page 10. ACM, 2014.

[2] Julien Bourgeois and Seth Copen Goldstein. Distributed intelligent mems : Progresses and perspectives. *Systems Journal, IEEE*, 9(3) :1057–1068, 2015.

[3] Stanislav Funiak, Padmanabhan Pillai, Jason Campbell, and Seth C Goldstein. Internal localization of modular robot ensembles. page 6, 2007.

[4] Seth C Goldstein and Todd C Mowry. Claytronics : A scalable basis for future robots. page 6, 2004.

[5] Robert Grabowski and Pradeep Khosla. Localization techniques for a team of small robots. In *Intelligent Robots and Systems, 2001. Proceedings. 2001 IEEE/RSJ International Conference on*, volume 2, pages 1067–1072. IEEE, 2001.

[6] Tran-Dang Hoa, Nicolas Krommenacker, and Patrick Charpentier. Localization algorithms based on Hop counting for wireless nano-sensor networks. In *Fifth International Conference on Indoor Positioning and Indoor Navigation, IPINâĂŹ2014*, Busan, South Korea, October 2014.

[7] Josep Miquel Jornet and Ian F Akyildiz. The internet of multimedia nano-things. *Nano Communication Networks*, 3(4) :242–251, 2012.

[8] Ling Mao, Jiapin Chen, Zhenbo Li, and Dawei Zhang. Relative localization method of multiple micro robots based on simple sensors. *International Journal of Advanced Robotic Systems*, 10, 2013.

[9] Dermas Moffo, Philippe Canalda, and François Spies. Resarch report on positioning within a system of mems ultra dense. Research Report RR-FEMTO-ST-MCS2, FEMTO-ST, July 2016.

[10] Mike Peasgood, Christopher Clark, and John McPhee. Localization of multiple robots with simple sensors. In *Mechatronics and Automation, 2005 IEEE International Conference*, volume 2, pages 671–676. IEEE, 2005.

[11] Renato Tinós, Luis E Navarro-Serment, and Christiaan JJ Paredis. Fault tolerant localization for teams of distributed robots. In *Intelligent Robots and Systems, 2001. Proceedings. 2001 IEEE/RSJ International Conference on*, volume 2, page 1061âĂŤ1066. IEEE, 2001.

[12] Hoa Tran-Dang, Nicolas Krommenacker, and Patrick Charpentier. Localization algorithms based on hop counting for wireless nano-sensor networks. In *Indoor Positioning and Indoor Navigation (IPIN), 2014 International Conference on*, pages 300–306. IEEE, 2014.

[13] Mark Yim, Wei-Min Shen, Behnam Salemi, Daniela Rus, Mark Moll, Hod Lipson, Eric Klavins, and Gregory S Chirikjian. Modular self-reconfigurable robot systems [grand challenges of robotics]. *Robotics & Automation Magazine, IEEE*, 14(1) :43–52, 2007.