Title: Control of a team of micro-robots for non-invasive medical applications

Key-words: team of micro-robots, external control unit, micro-robot with minimalist computing power, non-invasive medical processing

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Abstract

This paper deals with the control and the synchronisation of a team of micro-robots that performs a non-invasive surgical act into a human body. These micro-robots are very small sized (from ten to some hundred microns).
A single unit embeds the minimum of computing power and memory (minimalist electronics) to run a very light program, such as a finite-state machine. The mass effect of the joined micro-robots will allow to achieve the mission through a satisfactory way. The originality of this work being to consider a micro-robot as a disposable unit, which has to be as simple as possible, we need to combine reduced computing power with recent architectures.
Some kinds of mission are described and the most promising is detailed. Preliminary simulations support our approach.

1. Introduction

Today, many efforts are made to improve non-invasive surgery. Mini-robots and micro-robots are one of the answers.
On the first hand, mini-robots are centimetric sized. They are powered by batteries for some hours and are able to proceed inside the body. They are already in use in hospitals for example to inspect and to send images of the small bowel [olympus 08] or they are still prototypes under experiments like the biopsy and endoscopic capsule of the VECTOR project ([vector], [McCaffrey 08], [Duffait 03],…). Unfortunately, these mini-robots can not reach narrow areas, due to their large (!) dimensions.
On the other hand, micro-robots (about ten to some hundred microns sized) are still research objects. They promise to self displace ([Shoham 11], [Kosa 08],…) or to act on tumorous cells in an autonomous way [Pouponneau 09], or to treat coronary artery occlusion [Park 08]… The powering of such a kind of robot is still largely discussed by researchers (external energy fields [Martel 07] or boarded micro-storages like micro-fuel-cells, micro super-capacitors, or micro-radio- sources [Bogue 10a & b]). However, in most cases, one single micro-robot will not be able to fully achieve most of the missions to perform (tumor marking, drug delivery, tumorous cells killing, 3D imaging,…). Therefore, a team of micro-robots will be necessary.

2. Technical constraints

Bio-medical environment needs

Constraints related to the use of mini-robots inside a patient's body (surgery, for instance) will have to be taken under consideration. Some of them are :

- Non toxicity and non injury: No physical damage to the body and no chemical combination between the micro-robot and the cells of the body are allowed. Then, non aggressive elements are required and bio-compatible materials must be chosen
- Eliminability: Guarantee of the retrieval of the whole units of the team after processing, or guarantee of their safe destruction inside the body (by using absorbable materials for instance)
- Safety: No wrong operations are allowed
- Disposability: No re-use of the units of the team for another mission into another body

Safety needs : monitoring and control of a mission allocated to a team

Due to safety needs, we postulate the largest restriction to the decision autonomy of each unit of the team.
Because of the need to monitor the progress of a mission, a man-machine interface has to take place. This device will transmit acknowledgments of progress inside the mission planned by the physician. It will return to the

physician the sate of progress of the mission and some other information, like a number of still active micro-robots.

Microbotics constraints

Due to their very little dimensions, and due to their single use particularity, micro-robots must be minimalist in terms of mechatronics and in terms of computing capacity (costs savings through design and manufacturing). Therefore, only a few sensors and actuators can be embedded.

Embedded energy constraints

Once more, due to the very little dimensions of a micro-robot , the amount of embedded energy is very low. Then, each energy consumption has to be limited as much as possible.

3. Propositions to control a team of minimalist micro-robots for medical applications

The proposed work is the summary of preliminary research to control a team of micro-robots and to define their synchronization, as well as their control architecture. The originality of this work being:

- to consider a micro-robot as a disposable unit, which has to be as simple as possible ; then we need to combine reduced computing power with recent architectures,
- to consider the achievement of the mission through a satisfactory way due to the mass effect of the joined micro-robots.

3.1. Design choices

3.1.1. Architecture choices

We propose to coordinate the team of micro-robots by using a centralized controller. However, such a centralized controller will not be able to run each program of each micro-robot of the team. The communication link between the centralized computer and the units of the team would be overloaded. Then, each unit will have to run its own program. The control architecture must thus be hybrid between fully centralized and fully distributed.
Due to these constraints, a very simple data exchange system with the man-machine interface has to be used, in order to authorize the progress through each important step of the embedded program.

3.3.1. Micro-robots design choices

On the first hand, a micro-robot is a disposable unit due to single-use considerations and due to its loss eventuality, during the mission execution. On the second hand, a micro-robot has very small size. Then micro-robots have limited robotic resources.

Mechanically, each unit is unable to displace or direct itself (displacement is the result of body fluidic moves, in order to save motion actuators, save control surfaces actuators and save energy). It can perceive one particular characteristic (i.e. one single sensor) of the environment in the human body, and it can execute one or two single actions (like delivering a medicine, grip on a surface in order to stop its move). These actions don’t need a continuous flow of energy to run. A single pulse is enough.

From the micro-robot controller point of view, a single unit embeds the minimum of computing power and memory (minimalist electronics) to run a very light program, such as a finite-state machine (however, this program will be able to run different parallel tasks).

From the communications point of view, due to extreme simplicity requirements and due to energy consumption savings of each unit of the team, we forbid units to specifically communicate with each other. Then, micro-robots aren’t distinguished by a specific address and no addressed message will be sent. We propose to favour general diffusion of the messages. Then, a unit is able to receive and to distinguish one or two external signals, and to send one unique signal. This former one would be a continuous one if needed.

3.1.2. External controller choices and relationship between the main controller and the team of micro-robots

We propose to use a centralized computer to synchronize the actions of the micro-robot of the team and to provide the man-machine interface. However, due to the possible great number of units of the team, full

centralized control of the team isn't considered as relevant [Mataric 94].
When the received signal from the micro-robots is above a given threshold, it means that enough micro-robots are in the situation to perform the mission (the controller does not know which unit is ready or not, but the only number of them). Then the controller sends another signal to synchronize the execution. Only the micro-robots that are ready to perform it execute the mission. The other micro-robots are considered as lost. This loss can be temporary.
When the mission is done, all the micro-robots are assumed to be eliminated through natural ways. Some units can be lost through this way before they are ready to perform the mission.

3.2. Position of the proposed work

In this proposal, we are dealing with a kind of smart medicine, that is able to process only where it is needed, and when it is needed, instead to a common one, that processes the whole body (including the sane parts of the body) without coordination.
A typology of the different kind of possible control architectures is given by Jérémi Gancet [Gancet 05]. The architecture we propose fits his level 2 of decisional autonomy (Supervision and execution of a task is decentralized while coordination, task planning and task allocation are centralized).
Lounis Adouane [Adouane 05] proposed a work using the same designation (the control of a swarm of minimalist micro-robots), but it was based on intelligent, self-directed and high level communicative mini (and not micro) robots. More present works from the same domain [Benzerrouk 11] does not correspond to ours proposal for the same reasons.
Despite the possible great number of micro-robots of the proposed team, we don't deal with swarm robotics because no particular behaviour will emerge and since we do not look for emergent intelligence [Sahin 05].
Swarms robotics works compares their improvements to a reference of a non-communicating swarm of robots [Hsieh 09]. Then, our proposal can be considered as such a kind of basis.

4. Some mission examples

In order to perform different missions, the team of micro-robot has to be adapted in terms of design. However, It is not a good solution to modularize the parts of a micro-robot, in order to let the physician to configure each unit of the team because of their very little dimensions. In such a case, micro-assembly will occur, and will be extremely difficult to achieve. Then, if modularization occurs, it will only be useful for the manufacturer.
However, the team of micro-robots can be an heterogeneous one. Some elements of the team can be specialized, in order to minimize the complexity of each unit while increasing the functionalities of the whole team.

The surveillance mission

This kind of mission is the simplest one. Indeed, a team of micro-robots is wandering inside the human body. Its mission is to signal the discovery of a particular kind of cell. Each time this happens, the concerned micro-robot emits a brief signal. This allows to know if a particular kind of cell is present inside the body. The frequency of the received signals is an indication of the number of detected cells. This mission can last as long as some embedded energy is left and as long as micro-robots are present inside the body (elimination). Of course, the frequency of the received signal depends on the the number of remaining units too.
If the team can be resident into the body, this kind of mission can be useful to keep a watch on people at risk.

The spotting mission

This second kind of mission is based on the previous one. A team of micro-robots is wandering inside the human body. Its mission is to continuously signal the discovery of a particular kind of cell and to locate it. This last point is an improvement of the previous mission. If this occurs, the micro-robot clamps itself onto an obstacle (intestine or artery wall) as soon as possible and emits the signal. The main external controller has the capacity to determine where the emission of a micro-robot comes from. This allows to know if a particular kind of cell is present into the body, where these cells are and how much they are.
This kind of mission has the same purpose as the scintigraphy but avoids radio-emissions.

The drug delivery mission

This kind of mission is based on the previous one. However, the micro-robots have the additional ability to deliver a load of medicine. This is described in details in the next paragraph.

5. A mission study: the drug delivery case

The drug delivery mission is a typical case. A team of micro-robots is injected inside the body by the physician.

This team will spread inside the body according to the different fluidic moves. The body contains obstacles, onto which a micro-robot can bounce or clamp on as needed.
Some elimination zones catch every micro-robot that reaches them. Such a micro-robot is definitively lost.
An interest zone bounds the target, such as a tumor. area, where a particular obstacle lies (this obstacle is the target, like a tumor). This interest zone can be spotted by extra-body means, such as ultra-sound. After a sufficient waiting time, some units of the team are clamped on the obstacle to process, inside the interest zone, while other units are lost and some others are still moving.
The physician knows how many units are ready to process to the drug delivery through the power of the added emitted signal of the micro-robots already in place (ready units).
If the power of this signal is enough, the mission can be performed (the physician allows the next steps of the mission to the ready units).
If the power of the returned signal is too low, two options can be taken under consideration:

- the drug delivery can be delayed, in order to allow other micro-robots to reach the interest zone, and improve the number of units able to deliver the drug
- another team of micro-robot can be injected, in order to improve the number of ready units probability

Figure 1 describes the main controller and its attached devices, in order to perform the drug delivery mission, according to the above description.

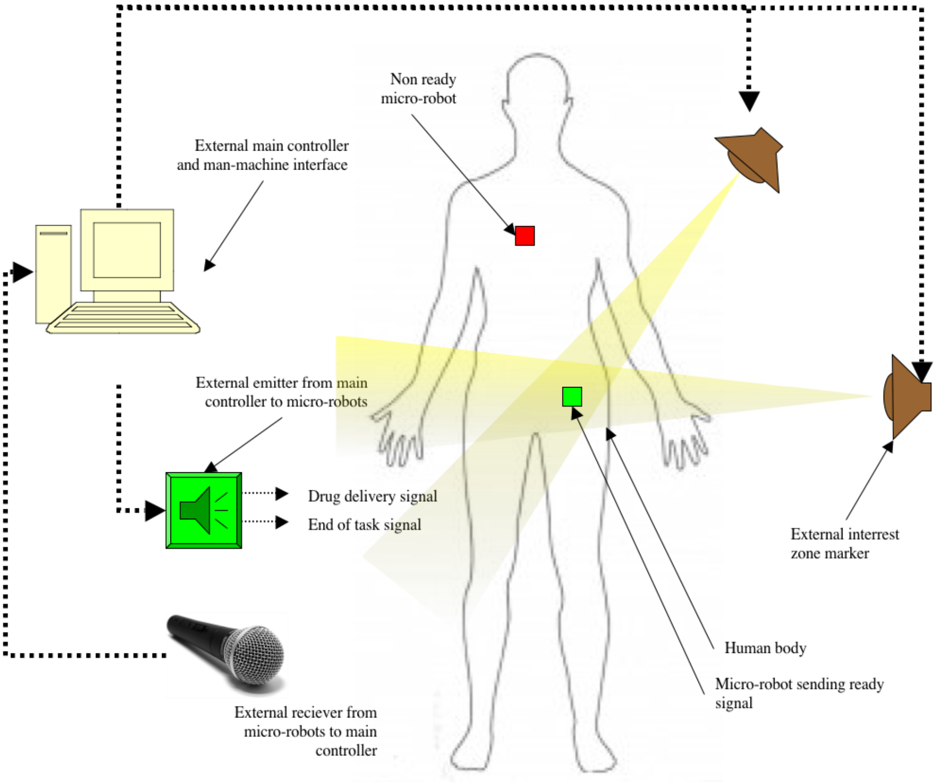

Figure 1. : External main controller and its equipments (drug delivery mission case)

Figure 2 describes the signal exchanges between the physician (through the main controller) and the swarm of micro-robots, in a successful drug delivery mission case.

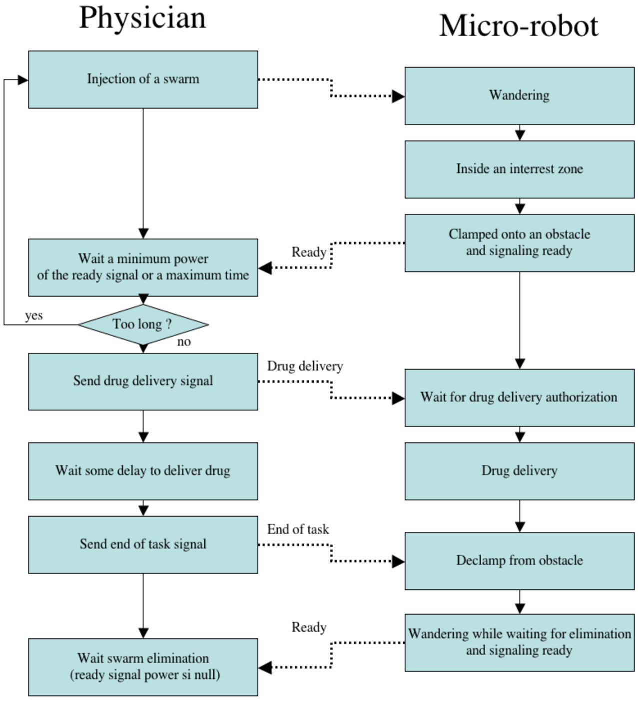

Figure 2. Interactions between the physician and the swarm (in a successful mission case)

Figure 3 describes the sensors and actuators that are required by each unit of the team, in order to perform the drug delivery mission. Inputs of each micro-robot controller are:

- a sensor to inform the controller if the micro-robot is inside an interest zone (inside an interest zone)
- a sensor to detect the bump onto an obstacle (obstacle detection)
- a sensor to detect if the micro-robot is into an elimination zone (inside an elimination zone)
- a sensor to receive the drug delivery authorization (drug delivery signal)
- a sensor to receive the end of task signal (end of task signal)

Outputs of each micro-robot controller are:

- an actuator to enable and disable the clamping system (activate clamps)
- an actuator to drop the medicine load (deliver drug)
- an emitter to send the ready signal to the main controller (signal ready)

Each input and output information is considered as a digital one. Each output has one single state of stability. The actuator that drops the load of medicine is a “one shot” system.

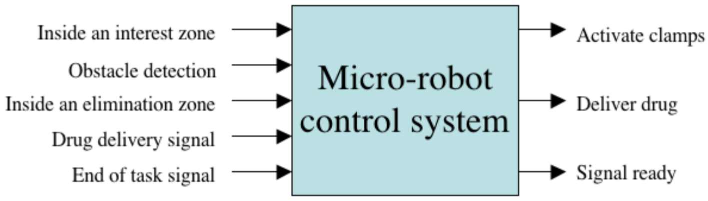

Figure 3. Micro-robot controller input-output (drug delivery mission case)

Each micro-robot embeds a simple finite-state machine (represented in Figure 4 with the Grafcet notation [David 92]) consisting of:

1. when activated, the controller waits the detection of an interest zone (step 0)
2. the controller waits an obstacle into the interest zone (step 1)
3. the controller commands the micro-robot to clamp onto the obstacle, signals the micro-robot is ready and waits the drug delivery authorization from the main controller (step 2)
4. still ordering the clamping, the controller orders the delivery of the drug load of the micro-robot , and waits the signal of end of the task (step 3). Then, each micro-robot in such situation had enough time to accomplish its part of the mission.
5. the controller allows to de-clamp from the obstacle, in order the micro-robot restarts wandering into the body (step 4). The controller waits the elimination zone detection while reporting to the main controller the mission was successful (reactivation of the ready signal)
6. the micro-robot is eliminated (step 5)

This textual description concerns the case the mission of the micro-robot is successful. Any other case is described by the different divergences of the Grafcet of figure 4.

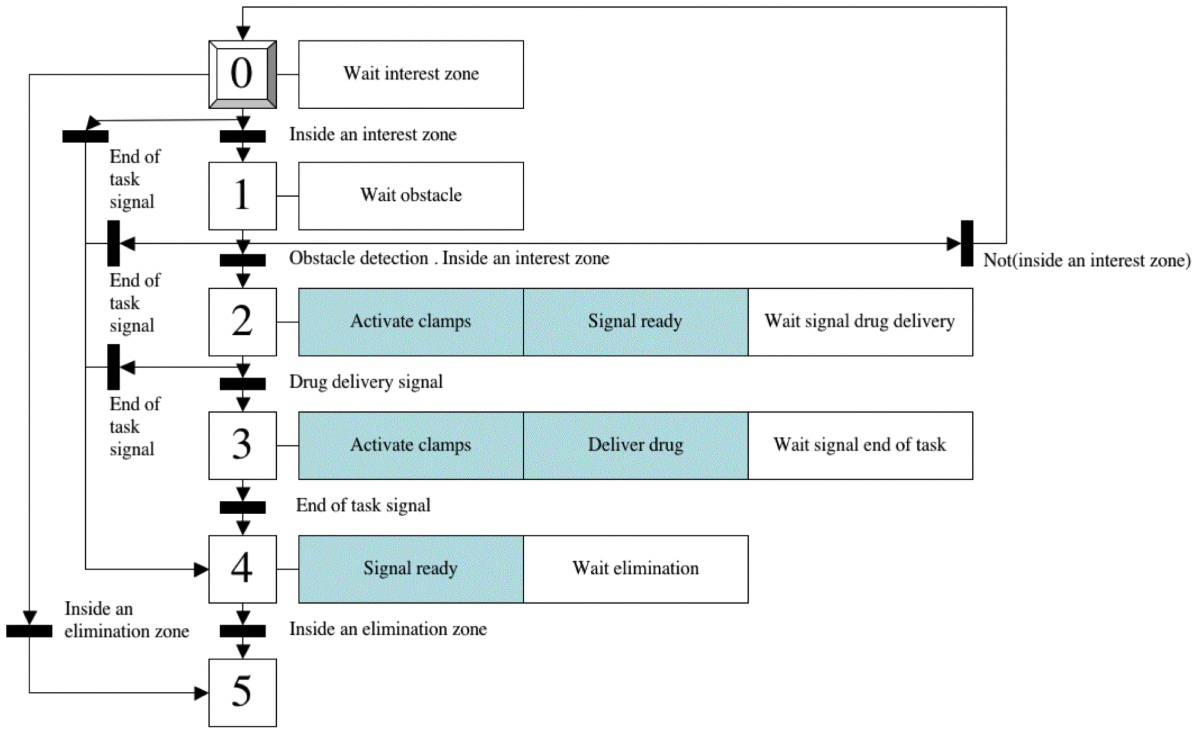

Figure 4. Micro-robot controller Grafcet program (drug delivery mission case)

This architecture was implemented in a multi-thread C++ simulator, where each component (micro-robot, controller and human body) is associated a thread.
Figure 5 is a screenshot that describes the modelling of the environment of the drug delivery mission.

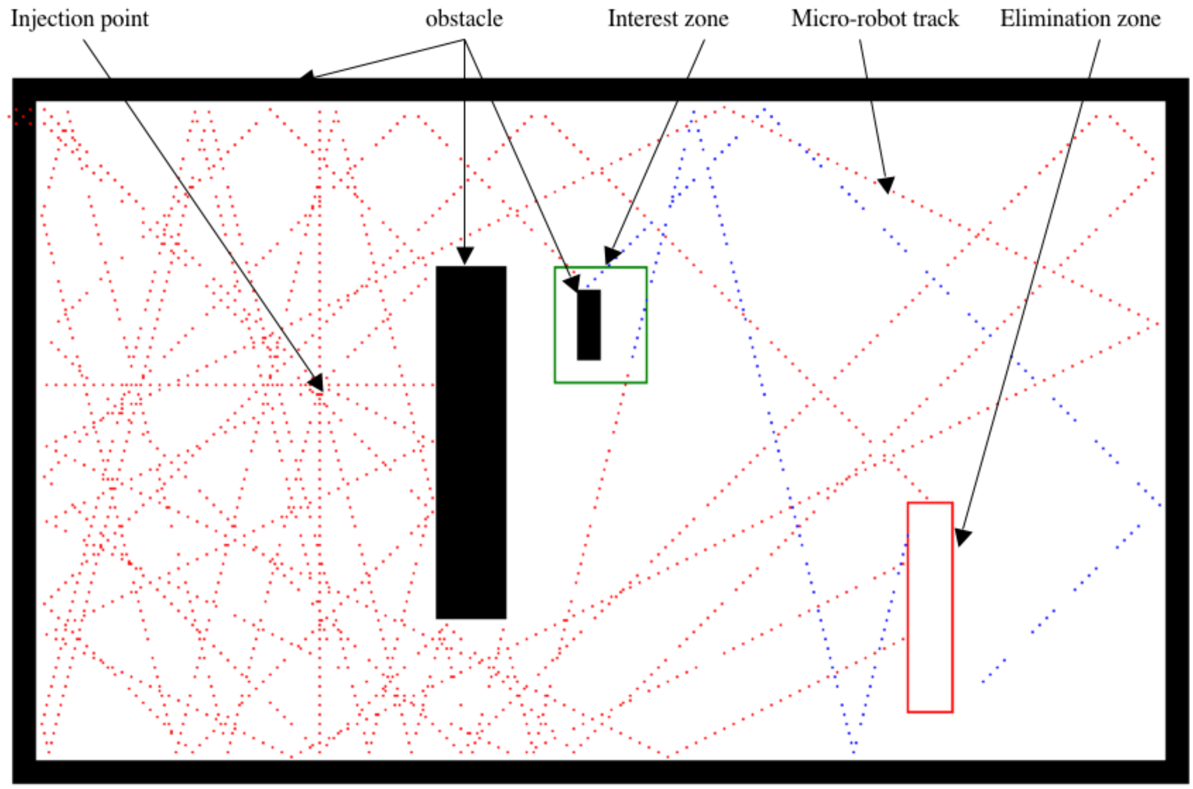

Figure 5. Modelling of the environment of a « drug delivery mission » issued of our C++ program

Figure 6 depicts the general evolution of the number of micro-robots along the time, when the team contains N_0 micro-robots at t=0.

- The green curve represents the number of micro-robots that reach the target, without elimination consideration. A maximum of $n_1<n_0$ units succeed, because some of them are definitely lost (they are wandering in the wrong direction, for instance)
- The red curve represents the number of micro-robots still wandering when including an elimination zone, without target consideration. A minimum of $n_2 > 0$ may be reached, due to the loose phenomenon.
- The blue curve represents the number of micro-robots that reach the target when considering an elimination zone. It isn't the mere sum of the two previous curves. This is due to the clamping action that fixes the micro-robots and then avoids the elimination phenomenon.

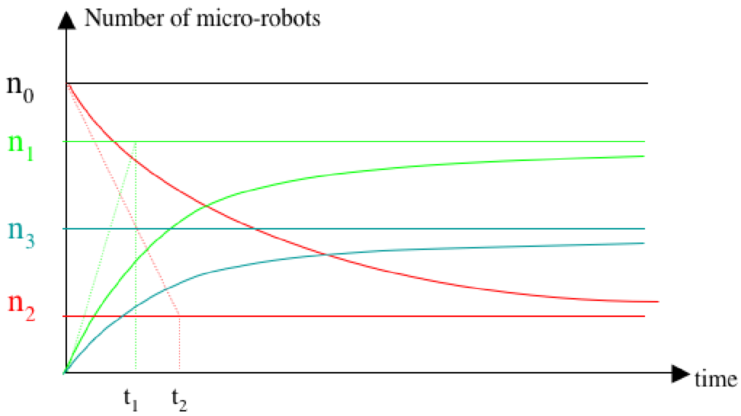

Figure 6. Evolution of the number of micro-robots of the team

Of course, the real evolution of these curves depends on the real conditions of the experiments (distance of injection point to the target, number of micro-robots of the team, direction and intensity of the body flows). However, our simulations validate the main shape of these curves.

6. Conclusions

We propose to investigate the control of a team of micro-robots that operates inside a human body. This approach deals with a kind of smart medicine that only acts where and when it is needed. This is done under the acknowledgement of the physician itself, who supervises and allows the different steps of the processing of a particular kind of mission.

Today, such micro-robots do not exist. Energy batteries, communication modules, among others, are not ready and the main controller itself is not reality (only coordinated programs exist into the simulator). However, in order to avoid most technical problems, the design of such micro-robots is chosen as simple as possible. In the same way, the embedded controller of each micro-robot is very simple, in order to use micro-electronic batch processes. However, micro-electronic will not be the only investigated way. Maybe, biological substrates will be useful.

Our further works will concern:

- First, some improvements of our simulator have to be developed. For instance, we need to use a more accurate model of the human body, with the fluidic moves that exist inside it, and the possible interactions between the body and the micro-robots.
- Secondly, we will imagine some other missions that can be allocated to the team of micro-robots. May be, this team may be more efficient if it is a heterogeneous one, with some specialized units. Then, what are the functions? Whose micro-robots will support them? How many micro-robots do we need to perform efficiently the mission? Then, will the team be more efficient if micro-robots can aggregate together in order to share their different skills and functions?

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