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Swarm of Nanobots in Medical Applications: a Future Horizon

Ali Moltajaei Farid
Dept. of Computer Science
University of Regina
Regina, Canada
afarid@uregina.ca

Malek Mouhoub
Dept. of Computer Science
University of Regina
Regina, Canada
mouhoubm@uregina.ca

***Abstract*—Many real-life applications rely on nanobot systems. These systems often imitate very simple tiny insects that can accomplish complex tasks. A swarm of nanobots can enhance the quality of life with the initial detection of diseases and treats patients with non-invasive surgeries. Since nanobots have highly controversial specifications due to quantum theory, this paper focuses only on innovative ideas as a future horizon. We define a list of objectives for coronary artery bypass. In this context, the swarm of nanobots reaches the limited flow artery and collaborates to remove the plaque. In addition, an online medical check-out system is stated in which swarm nanobots can be applied for initial disease detection. Finally, some ideas regarding medical check-out without visiting medical doctors and cancer treatments using this technology are discussed.**

***Index Terms*—nanobot, swarm intelligence. medical applications, non-invasive surgery, artery bypass, medical check-out, cancer treatment**

I. Introduction

With the ubiquitous growth in robotics, a wide variety of real-life applications rely on this technology [1–3]. One of these exciting areas is nano scale robot actuators. Nano scale products, such as nanobots, have attracted many researchers [4]. Nano scale medicine may be seen differently from a scientific perspective; chemists see the technology as the injection of nano materials into the blood vessels to improve the healing process of patients. For instance, [5] used a specific material to heal chronic cancer. The main drawback of this technique is the injection of material into the patient's whole living cells, which may have some side effects. Another approach is developed in robotics to resolve the issue, where nanobots will only focus on the specific impacted area of the body [6]. This will reduce the negative consequences of the treatment. Unfortunately, the current technology is not mature, and there are many open questions in this research context [7]. Still, it is not far from applying swarm robotic concepts to this topic which will strengthen and revolutionize the medical treatments for patients.

The nanobots market is expected to grow at a compound annual growth rate (CAGR) of more than 25 percent, between 2021 and 2029 [8]. Nanobots carry out a specific function and are 50–100 nm wide. They can be used very effectively for drug delivery [9]. Nanobots can be injected using an ordinary hypodermic syringe [10]. Nanobots are microscopic functioning robots with the ability to walk and withstand harsh environments [11]. However, nanobots suffer from technological limitations. For example, it is challenging to control a tiny robot in a blood vessel with a high flow rate of blood vessels. Researchers used strong magnetic fields to control nanobots to solve this problem. The generator of these fields is very bulky and requires a high volume installment above the patient [12]. In addition, nanobots have recently been controlled by ultraviolet light, and near-infrared wavelength [4]. The nanobot is expected to provide continuous monitoring and diagnosis from inside the body.

To the best of our knowledge, the swarm of tiny nanobots with actuation still needs to be devised [13]. However, there are some conceptual designs [14], and the concept of a swarm of nanobots is not achieved in real experiments [15]. While a collaboration among robots is crucial for swarm robotics, there are very limited technologies for communication on a microscopic scale. Some researchers suggested using different chemical tanks in nanobots to communicate with the chemical signals [16]. In addition, unlike the macroscopic swarm, in the microscopic swarm, the collision should not be a challenge [17]. Also, a number of simulators are developed for simulating these nanorobot motions [18] in nano scale [19]. Furthermore, there are limited reviews on physics in micro and nano scale for robotic applications [20]. Like any other technology, nanobots may have risks that are reviewed in [21].

Current technologies are limited in controls, detection, and actuators [22]. However, natural living species can be a good imitation of future swarm nanobots. Indeed, there is a recent European i-NANOSWARMS project which consists in studying the development of enzyme-powered nanobot swarms capable of self-propelling using bio-compatible and bio-available fuels [23]. In addition, swarm nanobots can improve diagnostic and surgical procedures. In general, people

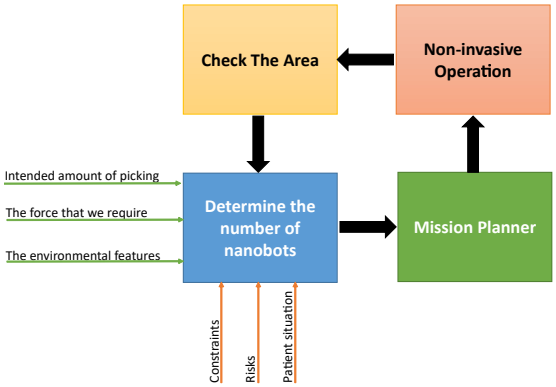


Fig. 1. The overall view of the proposed system.

Fig. 2. Major tasks for the unblocking or tumor removal missions' planner

Fig. 3. Major tasks for the check-out mission.

do not visit a doctor unless there are symptoms. However, many diseases do not exhibit symptoms at the early stage. In this context, a swarm of robots can always stay on the blood vessels and check the issues from the initial phases, which can be lifesaving. Also, many surgeries can be replaced by swarm nanobots that are safer and not invasive. In this way, only the patient opts for an invasive surgical procedure in case of emergency disease. In other instances, a swarm of nanorobots can slowly resolve the patient's disease.

II. System Design

The following are assumed to perform the swarm mission. There are n nanobots targeting a specific body part. Nanobots have access to their location and the location of the target. Additionally, each robot can move in the vessels in the same or opposite direction of blood circulation. Each nanobot within the swarm can communicate to its peers. Nanobots are sent to the body by capsules or injections.

With the above assumption, the designed system can be used for missions including: unblocking the artery, cancer tumor removal, and medical check-out. Target removal missions have a very similar idea to target tracking [24] while medical check-out can be seen as a specific type of surveillance and monitoring [25]. Figure 1 shows the general overview of the proposed system. There are four main stages: determining the number of nanobots, planning the mission to reach the area of interest, a non-invasive operation to collect the necessary material, and checking the area of interest for any reaction. This loop will continue until the area reaches the target stage based on the defined mission. The mission planner plans the proper path planning to reach the target area, swarm formation, and removal of the necessary material (Figure 2). The main tasks in a medical check-out are shown in Figure 3. The first task is appropriately using the current nanobots in the human body with adequate scattering to cover all organs at a particular time. Next is the monitoring of the organs and informing the doctor in case of an anomaly detection. As can be seen in Figure 1, many factors are used to determine the appropriate number of nanobots, including the complexity of the operation, risks, and patient's situation. In the following, we will describe these factors in details.

1) The intended amount of collected material. in a removal mission where a large amount of material might need to be collected, we need more nanobots and a sophisticated removal algorithm. On the other hand, in medical check-out, we will require a reasonable amount of nanobots to cover the body in an acceptable time.
2) The features of the area of interest should be considered. For instance, we might have higher flow rates or turbulence in some areas, which might add some constraints to the mission.
3) We need to cope with several constraints, such as nanobot mobility constraints, the maximum number of nanobots, and the maximum amount of safe picking up of the material.
4) Risks should be considered in a timely manner to improve the safety of the process.
5) Patients' situations should always be checked and monitored for any anomaly and improper reaction.

A. Problem formulation for removal mission

We assume we want to produce a gripper formation as a sphere with radius r. The radius depends on the size of the content of the unblocked area that we want to safely collect. This gripping sphere comprises several circles; each l layers are a circle with a radius between $[0, r]$ (as shown in Figure 6). It is important to note that in the $r = 0$ layer, only one nanobot will be located on the top and bottom to finalize the formation of the sphere. When producing a sphere with radius r, highest radius layers are formed before It is important to note that the formation starts with a double radius $2r$ and will be reduced to r after forming all layers. Next, the upper layer will form the circle with a radius $2(r - lc)$ (where c is a constant), continuing until the final layer with zero radius. After that, an upper half-sphere is formed, and all nanobots in each layer will move to create a sphere of the smallest radius, which will help the half-sphere act as a gripper for picking a tiny amount of blockage material. Afterward, the lower layers will be formed similarly to closing the gripper and avoiding dissolving the picked material into the blood.

1) The number of nanobots: The number of nanobots in each circle can be derived based on the sphere's radius. The proposed system requires a set of experiments to determine how many nanobots are necessary to pick a specific amount of specific mass. The radius can also be found based on online

learning techniques using the simulator or on historical date from past real-world experiments.

2) Avoid escaping the picked material:: The challenge of the proposed gripper system is to prevent dissolving the collected material in the blood. This can be done by closing the half-sphere with a complete layer. The closing layer is an accumulation of all nanobots that can build the upper half-sphere. This way, when the picked material is safe from potentially dissolving in the blood, the upper half-sphere can be gradually changed to a closed half-sphere. On the other hand, the formed sphere may have the ability to crush the material to very tiny pieces that can flow in the blood without any health concerns. In addition, if the material is too adhesive and dense, we will require to change (decrease or increase) the radius r repeatedly to push the material inside the sphere. For this purpose, we may use reinforcement learning to train how nanobots can act for different areas and materials. In this way, the nanobots first determine the mass density and, based on learning, will be able to complete the mission more efficiently. Learning capability in the swarm of nanobots makes the swarm more flexible and risk-free. It is more likely to deal with unpredictable situations in the mission, so higher flexibility of the system enhances the risk management for getting standard permission for the mass product [26].

3) Embedded processor: A swarm formation can be applied in many different scenarios in medicine. If the technology provides a proper type of processing on each nanobot, the latter can decide on the size of the gripper based on the patient's specific situation. Nanobots can form in a way that pushes the blocked area of the blood similarly to the current less invasive catheter approach, which will not lead to any wound on the patient's body.

B. The swarm's formation system

The main challenge of the removal system relates to performing a uniform distribution to form a number of circles which in three-dimensional will constitute a sphere. There are several approaches, including central and decentralized controllers. Centralized systems are easy to implement and have a strong global performance, while they suffer from low autonomy and large computations [27]. On the other hand, decentralized systems have high autonomy and quick response but are difficult for optimized formation and require a short communication delay for proper performance [27]. Centralized systems are less likely to be rigorous enough to use in such vital operations. In contrast, in a decentralized system, nanobots do not have a global view of their shape and can only communicate with their adjacent neighbors. Hence, there is a trade-off for choosing a suitable platform. The choice depends on the complexity of the operation as well as the specifications of the communication tool. The formation of robots in a circle shape is recently introduced in [28], where homogeneous robots build a circle. The only difference is that we will require a set of circles in this case. In [29], a decentralized approach has been introduced, leading to various pattern formations. Small robots have been used to produce a circle formation with a few sensing capabilities [30]. In addition, the time of formation is also crucial, as reported in [31]. Finally, our proposed system will work in an uncertain environment with a high flow rate which there is not much literature in this regard and requires attention.

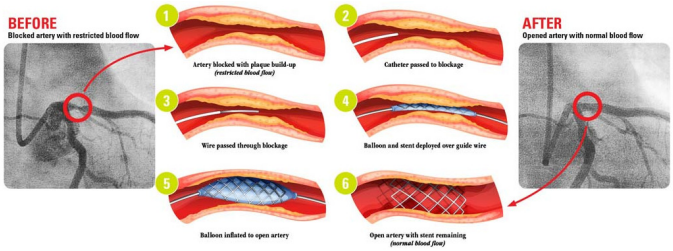


Fig. 4. The process of unblocking the heart vessel using catheter [34]

1) Decentralized sub-swarm based formation system: A decentralized system provides higher flexibility with the cost of a high amount of online computations. One approach for swarm formation of the proposed gripper consists in using a species-based optimizer. This optimizer can work with several sub-swarms that we call species. Each species has a seed that acts as a leader for the other species members (followers). A sphere is a set of circular layers. Each circular layer can be seen as a species. Note that previous work has been conducted on this topic in other robotic platforms [32]. Here, an evolutionary algorithm such as particle swarm optimization guides species to produce the desired output.

III. Applications

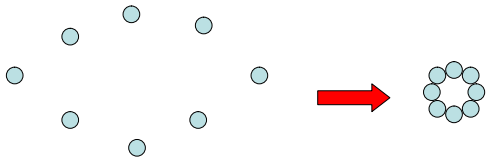
Three case scenarios are reported in this section. These scenarios respectively correspond to a non-invasive arterial bypass, a medical check-out, and a potential of cancer treatment.

A. Coronary artery bypass

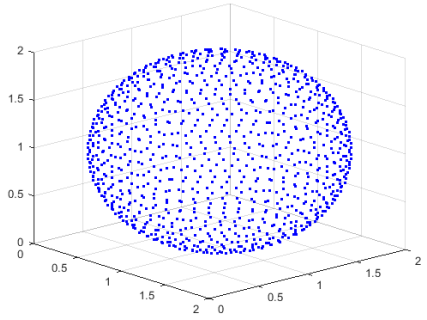
One of the common surgeries for elderly people is the coronary artery bypass grafting, in which the heart's vein is cleaned from fatty material within the walls of the arteries. Using swarm nanobots, this operation can be done without surgery with small injections of nanobots.

Current surgeries are invasive ablation techniques based on invasive entry into the body cavity to access targeted areas [33]. To minimize the invasion, catheters are introduced, in the body and far from the heart, with a tiny wound. While this procedure is less invasive, it cannot be applied for some people. The process of this surgery is shown in Figure 4. In this procedure, minimally invasive heart surgery involves making small incisions in the body to reach the heart using a catheter. When the catheter reaches the target area with restricted blood flow, a balloon will be inflated to open the artery.

The nanobots use the target removing strategy as a method to tackle the artery blocking problem. First, the bots will gather around the targeted area, and then they will try to defuse the vessel's fatty material within the walls of the arteries, in a timely manner.



(a)



(b)

Fig. 5. Illustration of the gripping process to free a very small content of unblocked area to the blood (a) a part of a sphere in two dimensional, (b) three dimensional.

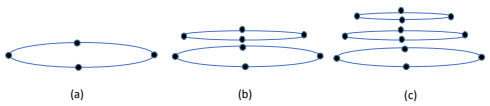


Fig. 6. Illustration of gripping formation with a set of nanobots in each circle (a) first circle, (b) second circle, (c) third circle.

A swarm optimization technique can be applied for this mission, using the following steps, reaching the target, aggregation, target removal, and delusion and self-destruction. In the aggregation step, based on the mission's complexity, a given number of nanobots aggregate in the target area. After forming a gripper, nanobots will remove a small number of plaques from the target. In the defusing step, nanobots defuse the plaques outside of the vessels. Nanobots form layers similar to Figure 4. if we have n nanobots. First, they randomly land on the blocked area and shape a gripper, as shown in Figure 5. Then they will tighten the angle of the gripper and move on vessels; this process may take a long time. In this scenario, the swarm requires the gripper's size. In the case of decentralized swarm decision-making, each swarm member has limited information about the vessel's current status, so the swarm can use well-known algorithms to decide the size of the gripper [35]. For safety reasons, we assume that the doctor sets the proper size of gripper. The gripper size depends on the blockage situation, the number of nanobots, and the unblocking process time. The latter depends on the severity of the blockage situation. After getting inputs from the doctor about the gripper's size and the preferred time for the nanobot unblocking operation, nanobots start the gripping by making several circles to build a half-sphere. After shaping a half-sphere, the gripping mechanism is used by all formed ring layers independently in a synchronous way, as illustrated in Figure 6. A small portion of the blocked material will grip as the half-sphere is formed. Next, other nanobots are joined to convert the half-circle into a full circle. This full circle will avoid any escaping of the plaques inside the vessels. Then, the formed swarm will carry the material to its destination to remove it from the body as a non-invasive approach.

B. Medical check-out

Often, the patient is aware of the illness when it is too late. For this reason, regular check-out is recommended, especially for advanced ages. Nanobots can play a better role in checking out the body and determining possible diseases earlier which can be lifesaving. For medical check-outs, the swarm should be in contact with a communication link. Since nanobots are always moving, we will need to devise an approach to maintain communication with the swarm. As swarms increase and become more dispersed, a gossip-based system [36] can be a good option. In this way, each swarm member is only in communication with a small number of nanobots in its adjacency, and the information eventually propagates from the adjacent nanobots to their neighbours. In addition, heterogeneity can be a good option in nanobots for improving check-out quality. Heterogeneity provides various types of nanobots with different capabilities in which each nanobot can perform a specific task. For instance, a nanobot can analyze the chemical constitution, while others can focus on detecting the color of the region to be explored. Since nanobots are in communication, the combined information will result in concrete details about the current status of the body organ. Finally, in some occasions, nanobots may lose their communication, and we will require to design a set of rules to maintain their functionality even in such cases [37]. It is worth mentioning that researchers have studied multiple swarms [38] and leader-follower swarms applications [39] in different missions to analyse their performances [40]. Regularly exploring the patient's body can be a precious option. This exploration will help people to keep healthy with regular medical checks. Here, the swarm collect medical data that are reported to the practitioners and doctors. The developed swarm can work for a few minutes or longer. After fulfilling the defined mission, the swarm might use a self-destruction strategy to meet safety measures.

A swarm of nanobots can investigate the body in a timely manner to detect any unknown issues like tumors and any other defects. Nanobots can perform this mission with random or more intelligent searches. The search of the swarm can be focused on specific organs and locations that might be infected instead of the whole body. For example, suppose a patient has a history of heart disease. In this case, nanobots will prioritize the kidney inspection and checking of the amount of sugar and related contents in the blood. This continuous inspection will help humans to be informed about diseases from the very early days, which can save cost and time for healing.

The blood test is another direction. Doctors can use the heterogeneous swarm with communication links for continuous

blood tests in the case of diabetes. In addition, heterogeneity can collaborate with different nanobots with different capabilities, increasing the system's efficiency. A human interface can be developed to access real-time information such as blood pressure and blood contents, and nanobots can fetch even urine content without laboratory tests. In this way, doctors can program the swarm of nanobots to go to the organ and inspect the area. The signal strength of the communication link between nanobots and the world is faint, so it might be helpful to design small adhesive antennas that can be located on the skin to amplify the signals and send them to the computing devices.

C. Cancer treatment

Cancer treatment highly depends on the status of tumors [41]. The Sooner the patient is diagnosed for cancer, the more chance for a successful treatment. Swarm nanobots can regularly check the human body, guaranteeing that nanobots can detect the disease from the early stages. In addition, most current cancer treatments target both healthy and unhealthy cells, leading to irreparable damage to living cells. In contrast, nanobots can detect tumors in cancer treatment and only do the treatment by targetting affected cells. In addition, in some types of cancer, i.e., lung cancer, it is tough to access the inside of the organ, while nanobots can go to the smallest part of the inaccessible organs. Nanobots can even remove cancer tumors from living cells with the gripping mechanism, in a timely manner, as reported in the previous section.

IV. Discussion

First, like many medical systems, there are many required test steps according to the International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO), including clinical verification of the technology and its side effects. We expect that standard organizations will introduce a new set of international standards soon to allow tests to be conducted to assess the effectiveness of swarm nanobots inside the body. Injecting nanobots into the body might have side effects, such as an unsuccessful removal. Also, unsuccessful collaboration among nanobots may lead to clutched vessels which might be dangerous. Likewise, since nanobots are very tiny compared to generally studied swarm robots, we might have unknown issues during the mission that need a lot of attention.

Cutting-edge technology does not provide a proper embedded processing power for the proposed application, which limits the decision-making. The short-term remedy might be using off computing techniques. However, to use the full capability of swarm intelligence methods we will require a proper processing on each nanobot. Nanobots suffer from communication links when using the current technology. One solution can be inspired by communication used in viruses, bacteria, and tiny-scale living species. Also, devising approaches to preserve the swarm within the communication field will be very complex as the body is very turbulent. The actuation design of nanobots still needs a lot of progress to preserve the stability of nanobots inside the turbulent medium of the human body. The implementation of the proposed system has two main aspects: software and hardware. From a software perspective, we list the main components as shown in Figure 7. Like for any complex problem, it is not easy to list all conditions that may happen in the body during a given mission. For this reason, half of the main steps should be based on online learning to make the system safe in unknown conditions. It is important to note that the online devising of new strategies takes a lot of work to guarantee that they are safe and require a vast amount of future research. For the offline side, a realistic simulator can help the system simulate the performance and learn from the simulation quickly and cost-effectively. From a hardware perspective, we will have processing, communication links, and sensors. In addition, one of the challenging parts is localization which might be based on the static antennas outside the body, similar to the ground positioning system (GPS). Finally, actuation needs a lot of work to build flexible, controllable, and observable nanobots.

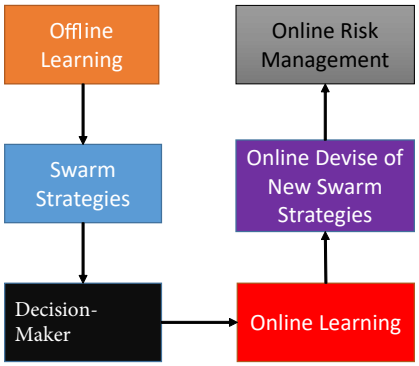


Fig. 7. The major software components

V. Conclusion

We proposed a few ideas on the applications of swarm nanobots in medical treatments. First, we used a formation of the swarm concept. In this way, we proposed a gripping mechanism in the swarm to replace current coronary unblocking surgery. This approach has some advantages including the fact of being non-invasive. Furthermore, no wound healing is required. Moreover, one can detect coronary problems from the initial stage, reducing the patient's risks. The gripping mechanism consists of nanobots to form a gripper to dissolve the blocking material from the coronary, or to remove a tumour. Also, we provide some ideas relating to medical check-outs where the disease can be detected in very early stages which can be lifesaving. Finally, the swarm of nanobots can only affect the tumors in cancer treatment without damage to the healthy cells. Developing the above ideas comes with several challenges. First, the proper controller is needed to produce a gripper by forming a nanobot circle. In addition, for picking a material by the gripper, nanobots should have intelligent motions. These motions should be planned depending on the substance complexity and the removing material's

specifications. Furthermore, the gripper should be safe for keeping the removed material without letting the material dissolve in the blood. For this reason, we may need a locking mechanism that keeps the gripper shape constant during the mission. Finally, designing proper tools to send the removed material outside the patient's body can be another future direction. Finally, nanobots are still very weak in communication, complicating the swarm designs. However, pheromone-based communication can be an option. Preserving the stability of nanobots in the blood vessels can also be very challenging with the current state-of-the-art.

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