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MICROROBOTICS: TRENDS AND TECHNOLOGIES

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ABSTRACT : *As time passes by, it lets leak out newer methods, ideas and innovations. Robotic concepts have been traced back to about the 4th century, and today's concepts have evolved even further, starting from tiny nanobots that could make their way into one's blood stream, and moving onto giant robotic arms. Microrobotics has also been a major trend in today's world. As we keep exploring as to how small circuits can actually get, it gives us a greater ability to focus on creating smaller microrobots. The purpose of this paper is to give an outline about the current advancements that have taken place specifically in microrobotics, and cover a variety of fields, including medical applications, insect behavior, microfabrication, micro assembly, positioning and also the microscale challenges that are faced with the fabrication and controlling of microrobots like the energy requirements and locomotion methods. Since the advancements in today's generation of microrobotics is very rapid, such that a massive amount of ideas have been conceived in a matter of a decade, only a small number of recent ones have been chosen to be a part of this journal.*

Keywords : *Micro-Robots, Microfabrication, Micro Assembly, Power, Actuation, Applications.*

I. INTRODUCTION

Two major discoveries in the world in 1595 and 1949 had shaped the future of MICROROBOTICS, the Microscope and the Integrated Circuits, one showed us the micro scale and the other how to work on it. MICROROBOTICS is a field that is getting a lot of attention today, not only from engineers specializing in the field, but also from other fields of engineering, scientists, hobbyists and even the general public. As time has passed, these robots have started off at sizes in millimetres, and have now reached sizes in the micro and nano scale of measurement. Miniaturization of technology has allowed us to push further for wider boundaries towards building smaller as well as more efficient versions of these, and it has proved that small things matter. As these microrobots become smaller and smaller, we discover more ways of applying microrobotics in more and more fields of matter.

Miniaturized robotic systems that make use of micro technologies are termed as microrobots. A microrobot may also be defined as one that possesses traits of a robot in the macro world and has some form of reprogrammable behaviour and is capable of adapting, the only difference to a macrorobot being the scale at which they are placed. The terms microrobots or microrobotics are also linked to robots that are able to handle objects and carry operations at the micrometer range. [1][2]

Microrobots due to their small size can have limited functionality and thus have to work in large groups or swarms in order to sense and affect the environment. The use micro and nanotechnologies in robotics not only reduce the size of robots but also results in reductions of the required recourses and lead to better performance of the robots.

The most challenging aspect in the development of microrobots is the fabrication of micro actuators and micro sensors which can give high efficiency and high stability. To overcome such problems scientists and researchers are combining technologies such as Micro/Nano Electro Mechanical Systems (MEMS, NEMS), nanotechnology and biotechnology [2][3].

The miniaturized size and integrations of devices and systems into one small system has the following advantages [4]

- Reduction in the required resources (mass, volume, power etc.).
- Many discrete devices and components can be replaced by Micro-electro mechanical systems (MEMS) and Nano electro mechanical systems(NEMS).
- The micro robotic systems are usually manufactured in “batch” process and this mass fabrication results in redundancy of critical parts in order to achieve a higher reliability during operation.

The overall cost of the whole systems can be reduced or a given overall cost increases performance with microrobotics.

II. MICROFABRICATION AND ASSEMBLY

Fabricating structures on a micro scale is the key for this field of robotics. With inspiration taken from MEMS, Bulk and Surface Micromachining are the major fabrication techniques for Micro Robots. MEMS devices take very less volume and power with negligible mass while integrating both the mechanical and electronic devices [5]. The techniques are very similar to those used in semiconductor device fabrications as the same accuracy is required in the microscale world as depicted below, Figure1.shows some mems fabricated gears next to a spider mite. Some of thecommon techniques are deposition of material layer via methods like oxidation, implanting, diffusion, etc., and even combination of them).

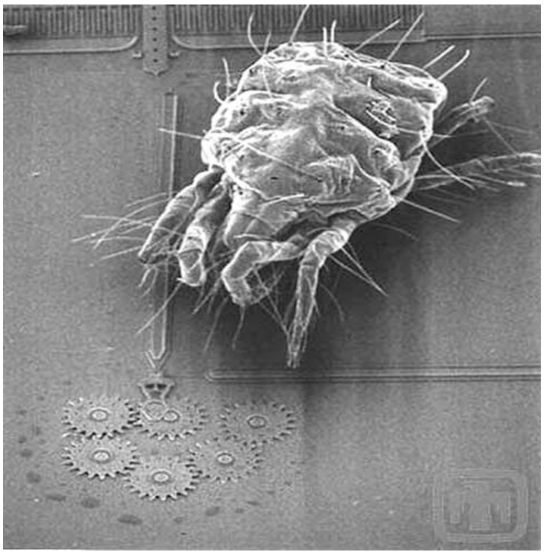

Figure 1. Size comparison of a MEMS gear & Spider Mite

Bulk microfabrication was the first MEMS fabrication technology. It employs fabrications on a single silicon crystal wafer, it is machined using etching and anodic bonding is done to work on the thickness of the silicon wafer. Unlike bulk, in surface microfabrication we selectively etch a silicon substrate to produce structures on top of the substrate [6]. To overcome the issues of material handling at the micro scale, laser micro machining is used. It is used to precisely process piles of composite material both in cured and uncured state. Laser micromachining creates a localized heating spot for cutting through the substrate. Because of the use of epoxy, it thus becomes important to decide if cured or uncured substrates are used.

A very fast solution to fabrication and assembly is under research currently and that is printable robots. This technique would lead to inexpensive and rapid prototyping. Each printable robot would generally be in absolute 2 dimensional flat sheets as inspired from the Origami [7].Therefore, assembly is the other stage of printable robots. These robots are self-assembled by folding. In order to achieve local and sequential folding, the substrate at the bends have to be actuated by local stimulus. The basic principle used here is the Joules heating law. The cross-sectional area can we varied as required to the magnitude bend and heat dissipation controlled properly. Serpentine Trace patterns are used widely in foldable robots because their pattern help increase resistance and at the same time also distribute heat all over the surface area [8].

Fabrication of micro robots is best when done in their final form using bulk manufacturing or even self-assembly methods like folding, but if the components are fabricated separately it is also possible to assemble all these parts. Manual methods like tweezers can be used to assemble parts of about 100µm in size.

All the equipment being used at large scale mechatronic systems become more challenging to manufacturer as the size reduces, this is because the surface effects start dominating the Newtonian forces [9]. This causes constraints on the performance and freedom of the bot depending on the materials available for fabrication and assembly at the MEMS scale.

The choice of materials affects the performance of the bot. Using high performance composite materials has provided a clear improvement in performance for micro robotics. Such materials overthrow common MEMS materials as they provide better fatigue properties and greater stiffness to weight ratios as compared to traditional materials. Hence increasing the overall performance [10].

Smart Composite Microstructures (SCM) technology is another fabrication technique which relies on the use of composite materials for the microfabrication [11]. The desired compliance profile is generated of the required geometry and material properties by the help of laser micromachining on the constituent laminae. Laser micromachining is an effective technique for making thin sheets with micron-scale actuators and articulated laminates. The structure of the microrobot is created by sandwiching polymers between face sheets of rigid composite materials (Fig 2). These layers can we actuated whenever any of the laminae are being electro activated.

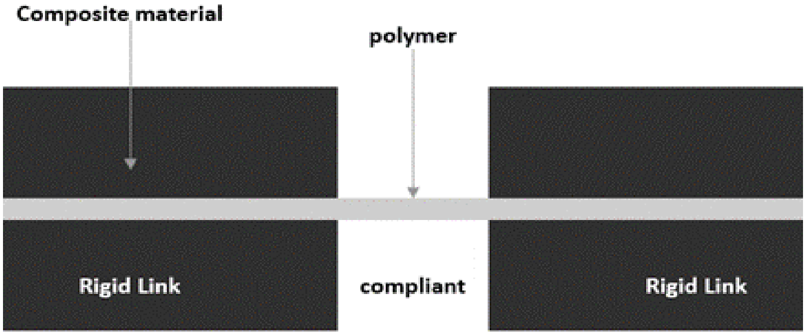

Figure 2. Composite layer and polymer sandwiching

Micro robots for biological applications raise a majorconcern over the biocompatibility of the micro robots.Most composite materials are not biocompatible. If the microrobot is being injected inside the human tissue, it should not cause any damage or infection to it.

III. POWER

As size of the components reduces at the microscale so does the volume capacity of the battery, hence supplying on-board power to a microrobot is extremely challenging. Other than biocompatible and chemically powered designs, most microrobots are powered by off board sources. The power required by the microrobot depends upon the size of the robot and the operating environment. Sensors and micro tools can function at comparatively lesser power. The other major technique of power sourcing for the microrobot other than on-board storages is providing wireless power sources such as Radio Frequency, Optical Power, and even energy scavenging. The use of Bacteria is one of the latest source of powering the mircorobots developed at the Drexel University [12]. The bacteria powered microrobot (BPM) consists of an SU-8 microstructure and active surfaces which work in conjunction to an array of biocompatible motors. The bacteria consist of a particular charge which can be easily manipulated with an electrical field, hence the activesurfaces of the BPM will be attracted towards them. Serratiamarcescens (Fig 3) is a bacterium which is considered perfect for this because they have a neutral negative charge.

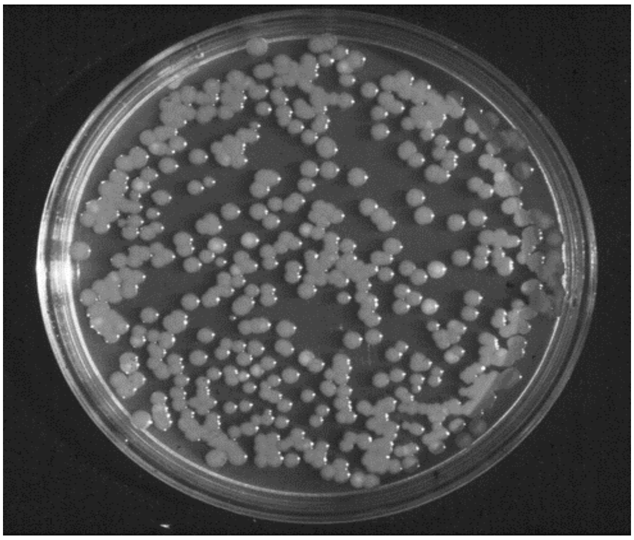

Figure 3. Serratiamarcescens[12]

Micro-supercapacitors are also being used as power sources because of the capacitors natural ability to charge and discharge like a battery. Micro-supercapacitors have over 1000x greater energy densities that are found intraditional electrochemical capacitors. These structures can generate capacitances in excess of up to 3 Fcm-2 [13].
3-D µBatteries are also available for the high performance power. These µBatteries have power densities ranging to 7.4 mW cm−2 µm−1. These power ratings equal to the best super capacitors or even above them, and is also much powerful than traditional micro-Batteries [14].

IV. CONTROL

Untethered mobile micro robots have seen many applications but another important question which arises is how we control these microrobots. Many techniques have been developed thus in both controlled and uncontrolled environments. The most common techniques on manipulation of the micro actuators are the use of magnetic and electric fields for controlling them from a distance. Some common methods are mentioned below.

A. Magnetic control

Magnetic fields can penetrate through most materials; therefore, they are the most well suited for the remote actuation of microscale components in not easy to reach spaces. it is very easy to produce magnetic field spatial gradients hence micro manipulations is possible. These forces are generated using magnetic coils or permanent magnets outside the working sphere of the micro robot. Researchers have developed many magnetic actuation techniques allowing custom work spheres and many degrees of freedom (DOF) with many control methods in both the open loop and closed loop control system environment. Ferromagnetism and paramagnetism are the two mechanism that are very dominant in all materials that are used for micro robots.
The magnetic flux through the electromagnetic coils is manipulated by adjusting the currents passing through the coils; this is done with the help of a computing device with data acquisition, the current signals are given through the linear electronic amplifiers with the option of having Hall Effect sensors for feedback depending upon the type of the control system. Up to 6 DOF (3R + 3T) can be achieved with independently controlled electromagnets for motion control in the 3D space [15].

B. Electric Field control

Manipulation of the Electrical field is a common alternative to the use of magnetic fields and discussed in some of the applications. The general idea is to generate attractive and repulsive forces on the bot to actuate it. Capacitive coupling allows the electrodes to directly drive the microrobot [16].
Experiments have been done in which the substrate on which the microrobot motion is to take place is provided with an array of electrodes. All these electrodes can be independently controlled which makes each point on the substrate addressable for the control of multiple microrobots [17].

Another method to actuate the microrobot is with the help of electro kinetic forces. Electrically active components are attracted by electro kinetic forces. The motion is controlled with the help of four or more electrode chambers filled with an ionic solution, surrounding the actuation work-area [18].

C. Light Propulsion

When light is focused onto a particular substrate it can be used to transfer its energy or momentum to the substrate, hence actuating the microrobot from a distance. Laser was used to actuate the bimorph limbs of a microrobot by causing thermal expansion [19].
The light intensity was controlled to vary the step size. Light also applies a pressure on the surface it falls which is considered negligible but at the micro scale it cannot be neglected. Sail boats were pressurized with a pressure of about 0.6 Pa which generated speeds up to 10µm/s [20].

D. Chemical Propulsion

The main actuating mechanism under chemical propulsion is actuation via chemical reactions. A micron scale jet is used to propel the components with the help of the oxygen bubbles which are being produced inside the jet tube because of chemical reactions with the liquid medium [21].

V. APPLICATIONS

A. MIMICKING INSECT FLIGHT

The flying abilities of several insects (as well as birds) and their aerodynamic features has been taken as inspiration for several concepts and inventions of tiny winged drones. Such robots are capable of moving much easily through complex environments thus making tasks such as monitoring and surveillance, search and rescue, and complete knowledge of environment [22], [23]. Artificial neural networks are also still in development.

Since simpler digital devices may not react in unpredictable situations, artificial neural networks built inspired by neural networking within insects tends to fix the problem [24].

Methods of actuation include actuation by electrostatics, electromagnetics, lead zirconium titanate (PZT), shape memory alloys (SMAs), which convert thermal energy to kinetic energy [24], [14], and even using rubber by means of flexible actuation [25], [26]. Sprawlita is a particular example of a microrobot using pneumatic motors, which require an external air source [27]. It is based on the natural movement of cockroaches. Brushed DC motors also find use in this field of microrobotics [27].

Piezoelectric actuators also find their purpose owing to the fact that they can be scaled to small sizes, and they can be put into a variety of configurations. The only challenges this method faces are high voltage requirements and the need to recover efficiency, since only a fraction of electrical input is converted to mechanical work [29].

It is also true that robots are being built with aerial and aquatic locomotive abilities put together. In such situations it is not useful to rely on airfoil designs [22], and hence this also involves observing the way various types of fish and sea insects move as well. Movable, flexible wing designs are in development.

Although many concepts have been brought up for insect-like microrobots, very few of these are capable of matching up to their naturally living counterparts, and this is due to the fact that these robots are so miniaturised, that energy requirements are very hard to account for in the case of longer life [24].

B. MICROROBOTICS IN BIOLOGY AND MEDICINE

When microrobotics is applied in medicine, it is usually so that magnetic actuators are preferred for the task in cases where these robots have to enter the bloodstream of an organism. Magnetic actuation also makes it possible for microrobots to be controlled wirelessly [28] [31]. Since most other methods involve usage of electrical energy for actuation, they will not be effective if planted in one's bloodstream. Using magnetism to bring about actuation can be applied almost anywhere in the body, and can also be used to treat sensitive parts of the body such as the eye [31]. Magnetic particles are most instrumental in drug delivery, as well as in fighting diseases such as cancer [32] and heart diseases. This also results in minimised reliance on surgical procedures.

Developments are also taking place to bring about magnetic actuation using magnetotactic bacteria, which comes under synthetic biology. Edward Steager et al. [30] describes using synthetic biology programmable sensors based at the cellular level, complete with memory and signal processing units. The idea mentioned involves building genetically engineered UV light-sensing bacteria with magnetic microrobots with a couple of set plans.

In the recent years The Institute of Robotics and Intelligent Systems researchers have developed micron sized micro robots that can powered wirelessly and controlled by magnetic fields. These microrobots are mainly used for robotic exploration within biological domains such as in the investigation of molecular structures, cellular systems, and complex organism behaviour.

Ferromagnetic materials have been used by the researchers at the IRIS institute to micro assemble three dimensional structural robots in the range of 2mm to 500 µthese robots respond precisely to torques and forces generated by magnetic fields and field gradients. Researchers at the IRIS have used micro fabrication techniques to fabricate robots in the range of 500µm to 200 µm. These robots have the capability to harvest magnetic energy from weak oscillating fields (1-6mT, 2-5kHz) using resonance technique.

At even smaller scale the researcher has developed microrobots called the Artificial Bacterial Flagella (ABF) (Fig. 4). These robots resemble the natural bacteria Flagella. They harvest energy from weak rotational magnetic fields. These robots are fabricated by vapour deposition of fine ultra-thin layers of element gallium, indium arsenic and chromium onto a substrate in a particular sequence. the ABFs have a magnetic head and with a use specific of software, the ABFs can be steered to a specific target by changing the strength and direction of the rotating magnetic field.

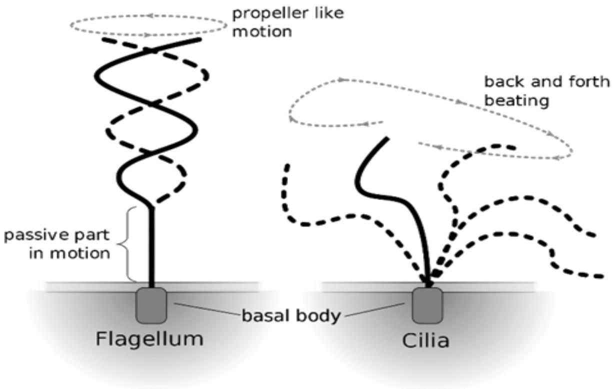

Figure 4. Flagella &Cillia Motions

The three micro robots mentioned above can be controlled precisely with as many as six degrees of freedom. These robots can be used to manipulate other micro and nano structures such as cells and molecules and can also be used as vehicles for target delivery deep inside the human body [33] [34] pre-programmed control of micro robots

C. CANCER FIGHTING ROBOT

Research for developing micro robots that can have the ability to target cancer cells have been going on since long. Scientists are finally coming up with micro robots than can be used for fighting cancers.

One such robot used to combat cancer is the Bacteriobot. It was developed by the researchers from the Chonnam National University in South Korea.

The bacteriobot is the world's 1st nanorobot for active medical treatment. These robots are genetically modified non-toxic bacteria attached to a bead that specifically attack tumour cells in the body. These robots are directly injected into the blood stream, diagnose and treat cancer by migrating and targeting tumours. The nano robot delivers the drug directly to the tumour and attacks the tumour leaving healthy cells alone. In this way it spares the patient from the side effects of chemotherapy.

The limitation of the bacteriobot is that it can only detect solid tumour forming cancers such as breast cancer and colorectal cancer. [35] [36]

D. MICRO ROBOTS IN EYE SURGERY

The eye is one of the most delicate organs in the human body. For years' research has been going on how to make eye surgeries more efficient and less time consuming.

One such discovery which redefined eye surgeries was the magnetically guided micro robot created at the Multi Scale Robotics Lab (MSRL) at ETH Zurich. Researchers at this lab named this micro robot as the OctoMag (Fig. 5). The size of OctoMag can be imagined as the size of few human hairs i.e. 285µm [38]. This robot is controlled externally and can carry delicate surgeries and removes the necessity of slicing the eye open for surgery [37].

The OctoMag is a magnetically manipulated system which consists of electromagnetic coils to wirelessly guide themicrorobots for eye surgery. Due to their small size theycannot carry batteries and motors so they are externally controlled using magnetic fields generated by OctoMag in 3D [38].

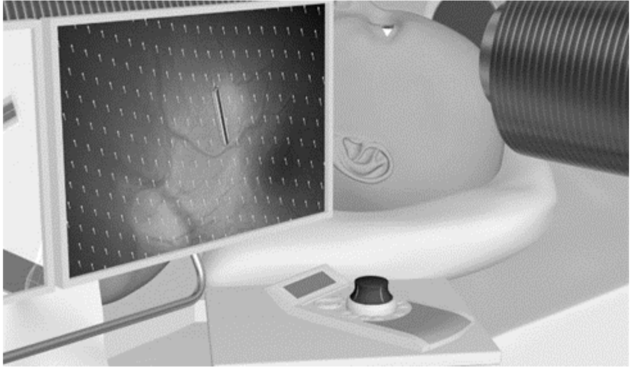

Figure 5. OctoMag [39]

The magnetic forces and torques generated by the OctoMag is physically restricted to single hemisphere to allow easy access for patients and physicians [39].

E. MICROROBOTICS IN SPACE

In space, miniaturisation of devices and systems and the introduction of MEMS and NEMS brings about a large number of advantages, such as reduced resource requirements and replacing bigger and more discrete equipment, thereby improving performance and efficiency and reducing cost, which is of major concern when considering space environments [40].

Another point to note is the various challenges that face microrobots put in this situation. These challenges include power, communication, and locomotion [40].

Power is always a challenge in microrobotics, as it puts limits to how small a device can get. Depending on the size and energy demands of the device, a variety of battery types can be used, which include coin cells, super capacitors and film batteries that are built using various polymer materials. From Table 1, it is very clear that thin film polymer batteries are very reliable and meet power, space, operating temperature and other requirements more suitably than the rest.

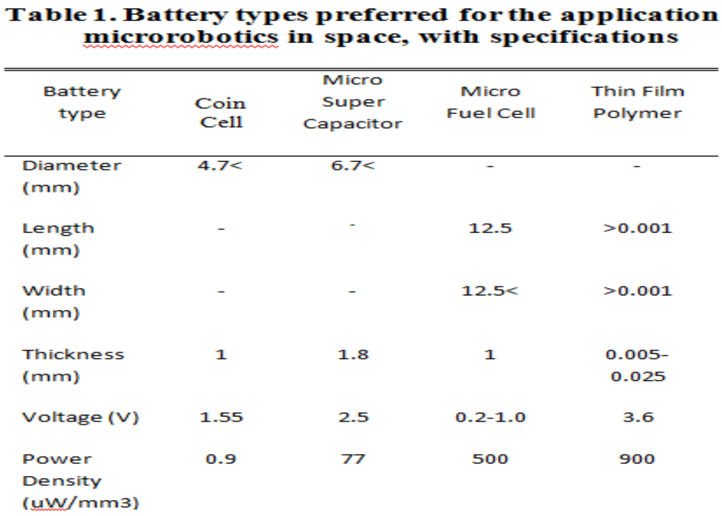

Table 1. Battery types preferred for the application of microrobotics in space, with specifications

Battery type	Coin Cell	Micro Super Capacitor	Micro Fuel Cell	Thin Film Polymer
Diameter (mm)	4.7<	6.7<	-	-
Length (mm)	-	-	12.5	>0.001
Width (mm)	-	-	12.5<	>0.001
Thickness (mm)	1	1.8	1	0.005-0.025
Voltage (V)	1.55	2.5	0.2-1.0	3.6
Power Density (uW/mm3)	0.9	77	500	900

Energy scavenging methods using induction, microwave energy transmission and photovoltaics are useful, but not in all scenarios and hence, must be planned out accordinglyLikewise, it is also necessary to plan out communication methods for microrobots in space, such as usage of radio frequency, coil induction and optical technologies, as they all have their drawbacks as well [40]. The same can be said for locomotion – walking, crawling, swimming or flying are currently the methods of motion being looked on, and as far as flying is concerned, since it involves considering gravitational fields, it takes a lot of research to create a working microrobot under these conditions.

Research is currently being undertaken at the Fremont Christian High School, Fremont, CA, United States, where the effects of microgravity on remotely controlled robots as well asmechanical devices is being studied by developing a robot known as NanoRacks-Fremont Christian High School-Micro-Robot or NanoRacks-FCHS-Robot (Fig 6).

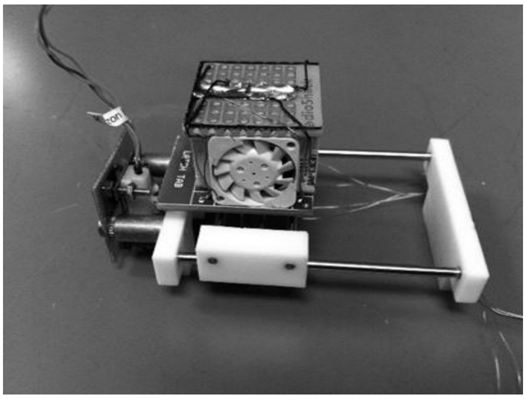

Figure 6. The NanoRacks-FCHS-Robot [41]

VI. Conclusion

Microrobots have been of great use especially in cases where size is of a great matter, such as the case in a number of medical applications. As time passes, the field of microrobotics increases in importance as the usage of microrobots has proven to have a huge number of advantages, such as abilities to operate with minimized interference with the environment and small size, besides others. While this paper mentions a certain number of applications, there are many more cases where microrobots have been used. Microrobots are capable of being applied in a variety of fields, and not just those that have been mentioned here, and this leads to the establishment of connections between microrobotics and the rest of the world.

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