Imperial College London
MRes in Medical Robotics and Image Guided Intervention

Individual Research Project
Platform for Microrobot Navigation

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1 Introduction

In the recent years, researchers were interested in magnetically actuated helical micromechanisms for use in a variety of biomedical applications such as cell characterisation, targeted drag delivery and vivo diagnosis (Peyer et al., 2013b). However, the extremely small size of the microrobots and the biofluid environment make the design very challenging. The two main difficulties are the power supply and finding suitable locomotion methods, as there are many cells, proteins and fibres in biofluids that prevent the motion of the microrobots. The common method of using an external magnetic field produced the most succesful result (Peyer et al., 2013c).

2 Literature review

The design of microrobots depends on their application. There is three common shapes of microrobots based on the rotary action; a helix, a screw and a twisted ribbon shape around its axis(Figure 1).

For the purpose of drilling into solid matter the screw and helix design would be more appropriate. However for the helical shape there is one pitch per rotation. There is also the consideration of penetrating a solid material from a fluidic environment. In the solid material, the rear part of the helical device will shift into the same location as the front part. In the fluidic regime this is not the case because of the low Reynolds number (Peyer et al., 2013b). The Reynolds number describes the ratio of the inertial forces versus viscous forces according the following mathematic formula;

$$Re = \frac{UL\rho}{\mu} \tag{1}$$

Where U is velocity, L is characteristic length, ρ is the density and μ is viscosity of the fluid. The very small length (L) and velocity (U) of the microrobots results in the very small Re ($Re \ll 1$). The motion in the environment with such a low Re can be described as being similar to a human trying to swim and move in honey. In the case of the helical microdevice,

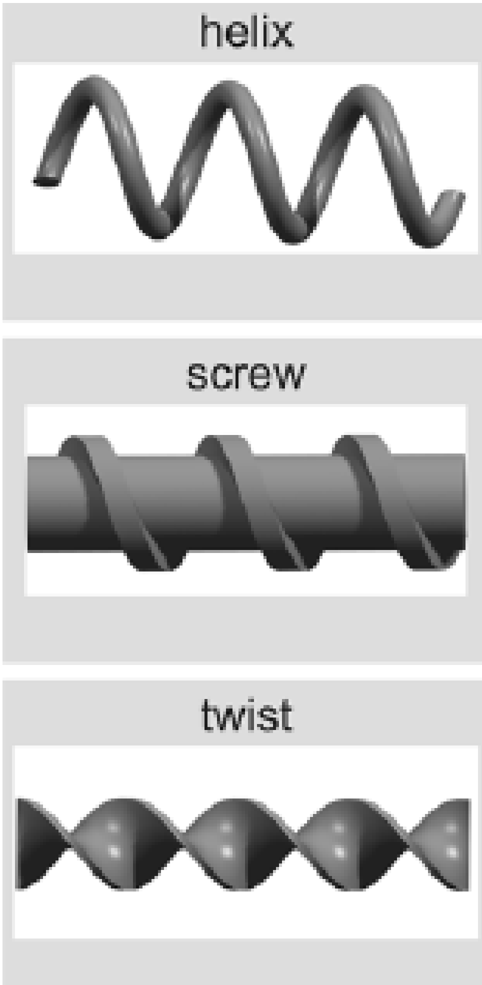

Figure 1: Three design of microswimmers. (Peyer et al., 2013b).

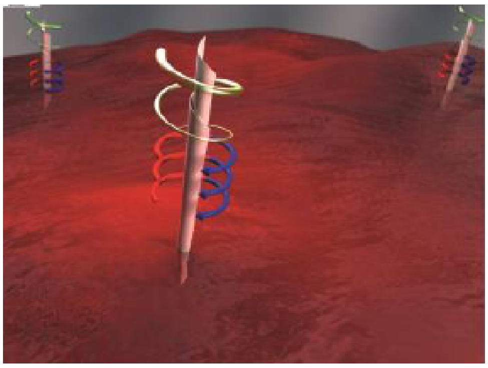

Figure 2: Magnetic microtube. Demostrating the drilling motion of the nanotubes under rotating magnetic field (Xi et al., 2013).

the helical rotation will not move forward in the same way as in solid matter because whilst the device is rotating in a fluid environment, it only moves by a small percentage of its pitch length per rotation (Peyer et al., 2013b).

There are a number of helical micro propellers that used external magnetic fields successfully and their method has been published but they usually require a complex setup (Qiu et al.). By learning from nature and mimicking the structure of live organisms, we can create successful scientific applications. The helical rotation of flagella and the travelling wave beat of cilia are two non-reciprocal propulsion mechanisms in microorganisms. Mimicking a rotating flagellum at low Reynolds number to generate an adequate torque to overpower the high viscous drag requires two main elements; a rotary motor and a power source (Qiu et al.). An electromagnetic rotary motor can be used in designing the helical flagella style microrobot that required a considerable current. However piezoelectric rotary motors are an alternative option that fit for miniaturisation but necessitate high input voltage. Hence, designing a microrobot with a combination of onboard powering source and motor is a challenging task (Qiu et al.).

Another approach for powering a micro robot is using the catalytic conversion of chemical energy into mechanical energy (Figure 2). In this method, the catalyst accelerates the disintegration of hydrogen peroxide and helps the self-propulsion of micro robot to pump the fluid to transport cells and colloidal particles (Xi et al., 2013). The catalytic tube (nanotube) is fabricated with a sub micrometer diameter. This technique is not applicable for the minimally invasive surgery (MIS) yet because the catalytic material used in the fabrication process of nanotubes is toxic and sustain viable mammalian cellular functions. Hence, biocompatible fuel is required to be developed in order to apply this technique in the live cell (Xi et al., 2013). Alternatively, the micro driller can be powered and controlled by using an external magnetic field such that changes in the frequency of the rotating magnetic field switch the rotational orientation of the micro tool from the horizontal position to the vertical one. The vertical orientation of the rolled up microtube and its sharp helical design makes the device suitable for drilling into biological tissue. In addition, the micro driller can be used for targeted drug delivery in MIS (Xi et al., 2013).

The type of microrobot design depends on its purpose and the desired task. For the purposes of drug delivery the tabular and helical lipid microstructure was successful and had good loading capacity and propulsion efficiency. The rotational motion of helical micro swimmers is one of the most effective propulsion methods in the low Reynolds number scenarios because it leads to translational motion. Microrobots with the microspheres structure perform similarly to the helical swimmers and are capable of swimming in the flowing liquid in microfluidic channel (Kim et al., 2013). More recently, a three-dimensional porous micro-niches designed for cell

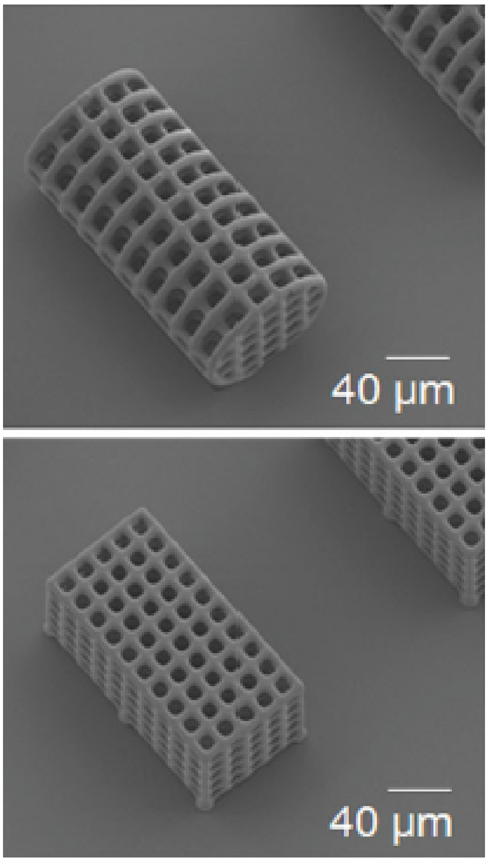

Figure 3: The image of two designs of fabricated microrobot under scan electron microscopy, cylindrical-shaped (first) and hexahedral-shaped (second) (Kim et al., 2013).

transportation purposes used photocurable polymer for its fabrication method. To improve biocompatibility for in-vivo application, the microrobot can be covered with a thin layer of titanium. In addition, the structures were layered with nickel for the purpose of magnetic actuation. A magnetic manipulator rotates and translates the microrobot wirelessly. Most in-vivo environments are three-dimensional, hence the 3D navigation will be required for the successful microrobot (Kim et al., 2013). One of the porous 3D structures used for cell adhesion and organ regeneration is called scaffold. Porous structures with the controllable porosity demonstrate improved characteristic such as high cell compactness and uniform cell distribution in comparison with the scaffold structure. Three-dimensional laser lithography is a state of the art technique to fabricate bio-scaffold structures (Figure 3). In this method a building unit is a single ellipsoidal spot, which form as a result of concentration of two laser beams. A pre-programmed path is followed by controlling the movement of a piezoelectric stage precisely to partly expose the photoresist. After removing the unexposed photoresist a complete three-dimensional structure of the microrobot can be formed.

There are two main factors that affect the movements of the microrobot in the external magnetic field; low coercivity and high saturation magnetization. Also, the motion of the microrobot is related to its size given the same magnetic field and as such, by increasing the size of the microrobot with the inflexible magnetic material volume, the velocity will decrease (Kim et al., 2013). The surface friction and the drag forces are two resistive forces that impede the microrobot motion. Hence, the input magnetic force must be sufficient to overcome these forces for microrobot manipulation. Furthermore, the weight of the microrobot required compensating in the z-direction by the magnetic field. The mathematic model below describes the microrobot translational movement;

$$\overrightarrow{F_m} + \overrightarrow{F_r} - \overrightarrow{F_g} = m(\overrightarrow{dv}/dt) \tag{2}$$

Where F_m, F_r and F_g are a magnetic force, overall resistive force and gravitational force respectively. M is a mass and v is a translational velocity of the microrobot (Kim et al., 2013).

Hexahedral microrobot and cylindrical microrobot can be developed using a similar method (Figure 3). However, because nickel is deposited uniformly on the surface of these microrobots, the Hexahedral structure has a greater amount of nickel deposited on its surface. Consequently, the magnetic force required for the hexahedral microrobot is greater than the cylindrical one while its translational velocity is lower than the cylindrical microrobots. Hence, the cylindrical structure is preferable for the purpose of minimising the resistive force against manipulation (Kim et al., 2013).

A magnetic field can be used for controlling teams of microrobots as well as a single one. Kim et al. proposed a method that used a combination of two magnetic materials to attain on/off magnetization of each microrobot. The overall control of the group of microrobots was achieved by managing the state of each agent. In addition, a second technique has been developed for three-dimensional motion of the team of microrobots in a fluidic environment. In the latter method, each microrobot is designed in such a way that it uniquely responds to the same input magnetic filed. Therefore, several microrobots can provide feedback position control in 3D system (Kim et al., 2013). An untethered spherical magnetic micromanipulator creates a locally induced rotational fluid flow field. The created rotational flow propels micro-objects in the flow area. The ream of microrobot could perform a complex task in micro-transport and micro-assembly (Kim et al., 2013).

The microrobot fabrication methods using biological material resulted in increased capability and improved locomotion. In comparison, the materials such as silicon, silicon dioxide and metals are brittle and have considerable limitation over biological substance (Vogtmann et al., 2013)).

In another study (Tottori et al., 2012), a helical microrobot designed to swim in a low Reynolds number fluid, a 3D direct laser writing method was applied as the preferable technique for fabrication. This fabrication method allows flexible design of microrobot in which two designs are selected to run the experiment and demonstrate the result. The first structure is a bare helical structure and the second one is the helical shape with the microholder attached at the end. Both designs will generate the corkscrew motion in a fluid environment when there is sufficient magnetic filed. The second design (device with the microholder) is capable of transporting a microobject accurately to the target (Tottori et al., 2012). The fabrication process consists of the three stages that are fairly similar to the work performed by Kim et al.. In the first step, direct laser writing in negative tone photoresist wrote the helical device. The developer then removed the unpolymerized photoresist. Finally, the developed helical swimmers were left for drying out and then coated in a thin layer of titanium and nickel for biocompatibility and magnetic actuation (Tottori et al., 2012).

In Tottori et al. experiment eight different designs of microrobots were proposed and tested. The uniform static magnetic field was used to explore the magnetic shape anisotropy and the magnetic actuation was monitored in the rotating magnetic field. In the static magnetic field the set of microrobots with the helical angles ranging from 45° to 70° were suspended in the deionised water.

This showed (Figure 4) that a smaller helix angle θ results in a less misalignment angle α because microrobots longest axes will be aligned to the direction of the external magnetic field. However in helical microrobot with the larger helix angles the magnetization direction

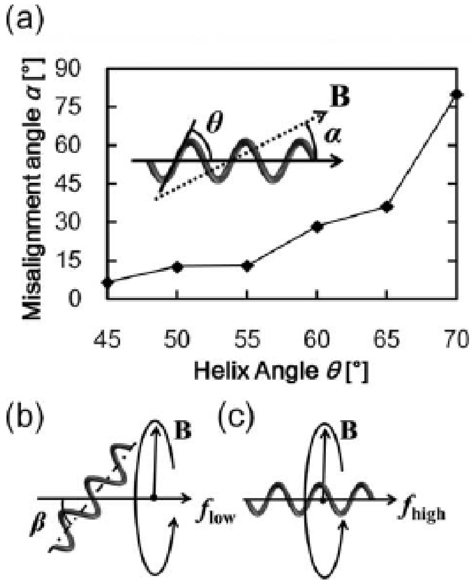

Figure 4: (a) The misalignment of helical angleα with differnt helix angle (b) the oscillation behaviour of the microswimmer with the high and low frequencies (Tottori et al., 2012).

would change to the radial axes of the helix (Tottori et al., 2012). In the rotating magnetic field, the micro helical swimmer exhibits different behaviours depending on the strength of the applied frequency in the fixed magnetic field. At low frequencies the micro helix wobbled around the helical axes, however by increasing the frequency the oscillating behaviour changed to the corkscrew motion. This is similar to characteristics observed on the microrobots with the incorporated microholder (Tottori et al., 2012).

The velocity of helical micro swimmers depends on their size and shape. The linear relation was observed between the input frequencies and swimming velocity of the micro swimmers. The outcome of the comparison between three microhelixs with the same helix angles showed that the microhelix with the greatest diameter has the highest speed, in accordance with the following formula;

$$U = \frac{(C_n - C_1)\sin\theta\cos\theta}{2(C_n\sin^2\theta + C_1\cos^2\theta)}(d\varpi) \tag{3}$$

Where C_n is a drag coefficient perpendicular to the filament and C_1 is a drag coefficient parallel to the filament. ϖ is the rotational frequency and d is the rotational diameter of the helix (Tottori et al., 2012).

The important role of helix angle in the magnetization structure of helical micro swimmers was confirmed by Peyer et al., who again used direct laser writing as a fabrication method but applied that on the magnetic polymer composite (MPC). The MPC are non-cytotoxic and showed super paramagnetic characteristic because magnetic material was already included in the polymer.

The relationship between the torque T_d, the drag force F_d, the object's velocity U and rotational speed ω is linear and modelled by 6×6 resistant matrix as below;

$$\begin{bmatrix} F_d \\ T_d \end{bmatrix} = -\begin{bmatrix} A & B \\ B^T & C \end{bmatrix}\begin{bmatrix} U \\ \Omega \end{bmatrix}$$

Where A, B and C are matrices 3x3 and only depends on the object's geometry and fluid

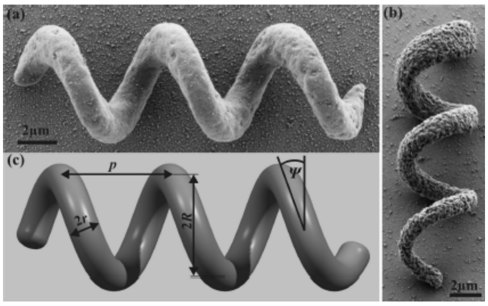

Figure 5: The prototype of microhelical device. (a) Scanning electron microscopic image of the micro polymer composit with the 2 vol.% nanoparticle fill factor and (b) 4 vol.% of nanoparticle fill factor. (c) The CAD model shows all the parameters required for the microhelical design (Peyer et al., 2013a).

velocity. There are few methods in use to model the resistance matrices and low Reynolds flow such as the method of regularized stokeslets, the boundary element method and the method of fundamental solution . In designing a microrobot the main parameters required to concentrate on are the helicity angle ψ, the helix radius R, the pitch p and the filament radius r as can shown in Figure 5 part (c).

The micro robot using torque-driven method is more favourable than the force-driven method because their rotation is based on applying torque rather than a force to pull the device (Peyer et al., 2013a).

Another design of microswimmers was inspired by the function of magtigonemes in nature (Tottori and Nelson, 2013). A smooth flagellum moves against the direction of the propagation of the flagellar wave. However, the flagellum covered by magtigoneme propels in the same direction as the flagellum wave (Figure 6). Mimicking the structure of flagellum and using 3D lithography and electron beam evaporation formed the fabrication method in this microswimmers.

The anisotropic viscous drag on flagella is an important fact for locomotion in low Reynolds number fluid. Flagella movement in the opposite direction of the flagella wave can be explained by this factor so as the viscous drag coefficient perpendicular to the flagella is greater than the viscous drag coefficient parallel to the flagella (Tottori and Nelson, 2013). The fabrication process consists of two stages. Initially the core structure of the artificial helical microswimmer is printed using 3D lithography and then electron beam evaporation is used for ferromagnetic thin film coating (Tottori and Nelson, 2013). Performance of each microswimmers (with different design) can be scanned by the scanning electron microscope (SEM). After the fabrication process is completed, the next step is releasing the structure in the deionised water using the tungsten probe. The tank with deionised water is installed in the middle of the three-axis Helmholtz setup. The rotating field, i.e. rotational frequency, field strength and angles that defined the rotational axis can control by the current in the coil. The helical microrobots rotate synchronously with the rotation of the magnetic field and move forward and backward accordingly (Tottori and Nelson, 2013).

The displacement of the microswimmer along the rotational axis can be measured and the result used to calculate the average velocity of the swimmers. There is a linear relationship between an input field frequency and swimming speed. According to their result (Tottori and Nelson, 2013), a propulsive force generated by the mastigoneme is in opposite direction of the force generated by the main helical filament.

The swimming velocity of a mastigoneme helical swimmer is illustrated in (Figure 6) and can be estimated by the following symmetric propulsion matrix;

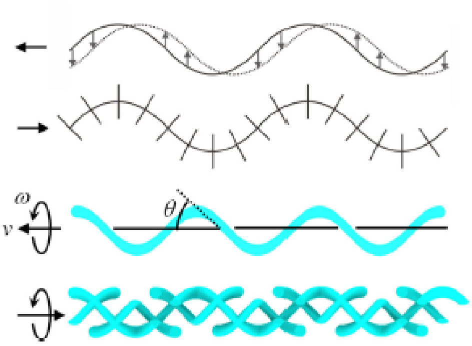

Figure 6: The structure of the smooth flagellum and a mastigonemes flagellum. (Gao et al., 2013).

$$\begin{bmatrix} F \\ T \end{bmatrix} = \begin{bmatrix} A & B \\ B & C \end{bmatrix} \begin{bmatrix} \nu \\ \varpi \end{bmatrix}$$

Which angular velocity is ϖ, valocity ν, external torque T and external force F. The propulsion matrix has two main components; one is for the main flagellum and the second is for the mastigonemes. After solving both part of the propulsion matrix, the velocity of the microswimmers is given by the equation below;

$$\nu = \frac{(B_1 + B_2)}{A_1 + A_2}(\omega) \tag{4}$$

Where

$$\begin{aligned} A &= A_1 + A_2 \\ B &= B_1 + B_2 \end{aligned} \tag{5}$$

However, this velocity is only valid if the external force is zero. The proposed design (Tottori and Nelson, 2013) is rigid and an external stimulus may be used to regulate the swimming speed and direction if the swimmer can fold and unfold their structure.

One of the most challenging aspects of designing a robot on a very small scale such as a nanorobot is simplicity. The reason is, integration will become unfeasible on that scale if the design is complex, hence the development of the nanorobot or even microrobot should be based on the essential functionality, avoiding any unnecessary components. Helical flagella and cilia are two well-known microswimers in nature that their functionality employed for motion generation in artificial microrobots (Figure 7). Their motion generation mechanism relies on the drag imbalance of a cylindrical element and non-reciprocal motion (Gao et al., 2013).

In 2007, Bell (Gao et al., 2013)presented the first artificial bacteria flagellum microrobots and then Zhang characterised them in 2009 (Gao et al., 2013). This artificial microrobot was formed of two components; a rigid helical tail and a soft magnetic metal head. The head diameter was $2.8\mu m$ and its length was $30 - 100\mu m$. The size of the head is $200nm$ thicknesses and its length varied from $2.5 to 4.5\mu m$. Since then, other scientists proposed a slightly different design structure, that all have the rigid helical tail structure. However, in some cases the magnetic materials is used in the device tail rather than the head (Gao et al., 2013). However, the fabrication of the microrobot was the main problem that recent fabrication methods offer a feasible solution for (Gao et al., 2013).

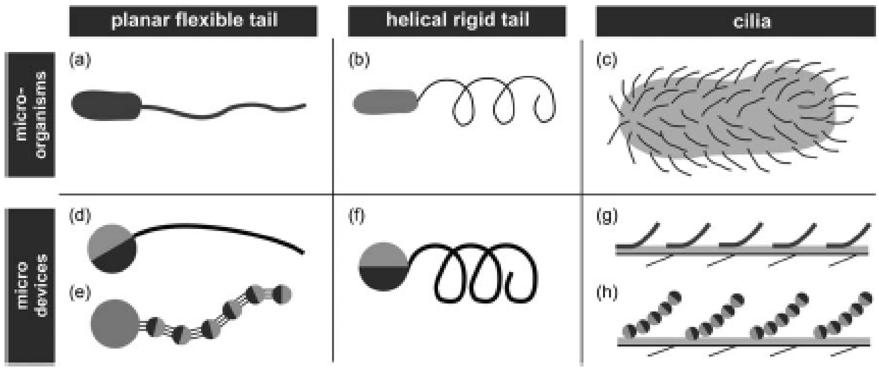

Figure 7: The illustration of both flagellum and cilia shapes and microdevices mimicked the flagellum and cilia structures. (Peyer et al., 2013c).

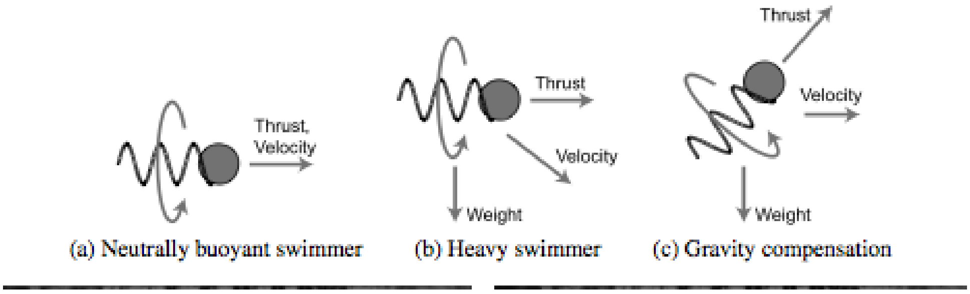

Figure 8: The effect of the gravity on the microrobot motion direction and gravity compensation . (Mahoney et al., 2011).

One of the problems with a man-made nature inspired micro device is that they are usually heavier than their natural counter part. In the case of microrobots, the navigation methodology should compensate for gravity to avoid sinking and enable velocity to be controlled wirelessly. Mahoney et al. described an algorithm for helical microswimmers velocity control plus gravity compensation. In the proposed model the correct pitch angel and rotation speed is calculated to achieve the commanded velocity (Mahoney et al., 2011).

The helical microstructures are not limited to having flagellum-like structures and microbots with general cilia-like feature have been designed. Gao et al. observed the helical microstructures that imitates spiral water-conducting vessels of different plants.

The fabrication process involves coating isolated spiral xylem vessel plant fibres within a (Figure 5) thin magnetic layer. Xylem tissue transports the plant's required food such as water and other nutrition from the root to the leaves all through capillary action (Mahoney et al., 2011). Use of plant material in this method result in simple three-dimensional microswimmers fabrication and biocompatibility. In addition, the magnetic cover helps to ensure accurate directional control and high-speed propulsion. Therefore the fabrication processes were extremely simplified as the main component of the helical microswimmers is from nature and more than a million individual micro helical can be made from a very small section of the plant stalk (Mahoney et al., 2011).

Using mechanical stretching can control geometric variables of the helical vessels such as the pitch and helix angle and hence plentiful helical microswimmers can be reproduced. The final shape of the helical microswimmer is determined mainly by the initial diameter of the

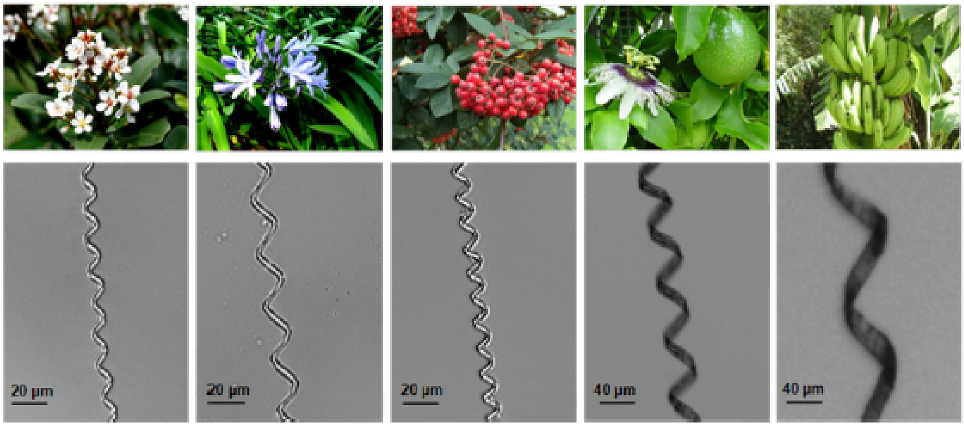

Figure 9: The shape of the Xylem in differnt plants . (Mahoney et al., 2011).

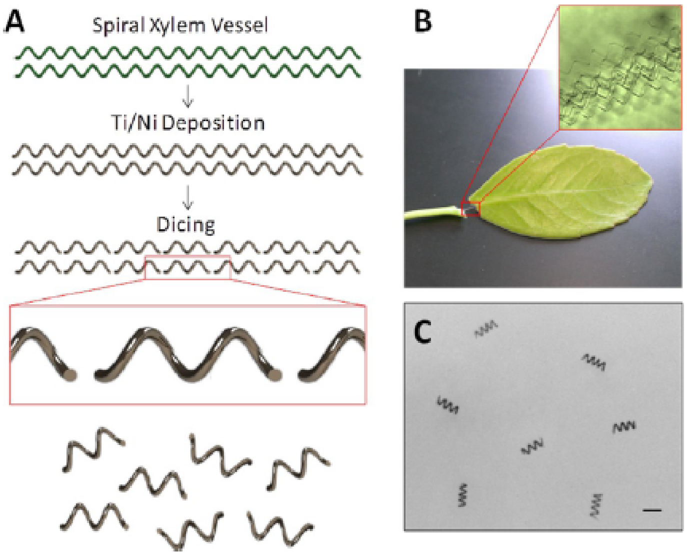

Figure 10: The shape of the Xylem in differnt plants (Gao et al., 2013).

unstretched spiral vessel. The process of stretching helical plant structure was performed via plastic deformation so that the number of helical turns are constant and tensile stretching of the plant fibre stretching is negligible (Mahoney et al., 2011).

The method used for precise propulsion control and characterising the locomotion behaviour of the plant-based microswimmers is similar to the method applied in Gao et al. study.

According to Gao et al. experiment, the plant-based microswimmers exhibited high speed movement in raw biological medium such as pure human serum under the rotating magnetic field. Moreover, the increased velocity of the biological fluid has a minor effect on the plant-driven microswimmers, whichis an important advantage of this microdevice over the common microrobots.

Jellyfish-like swimming robot is another robot design that scientists were interested in because of its unique swimming style. Different type of actuators are used to model jellyfish-like swimming robot such as shape memory alloy, ionic polymer metal composite. However, these jellyfish-like robots were unable to swim freely in three-dimensional space due to small propulsion force and were restricted from the power supply wire. Therefore an external magnetic

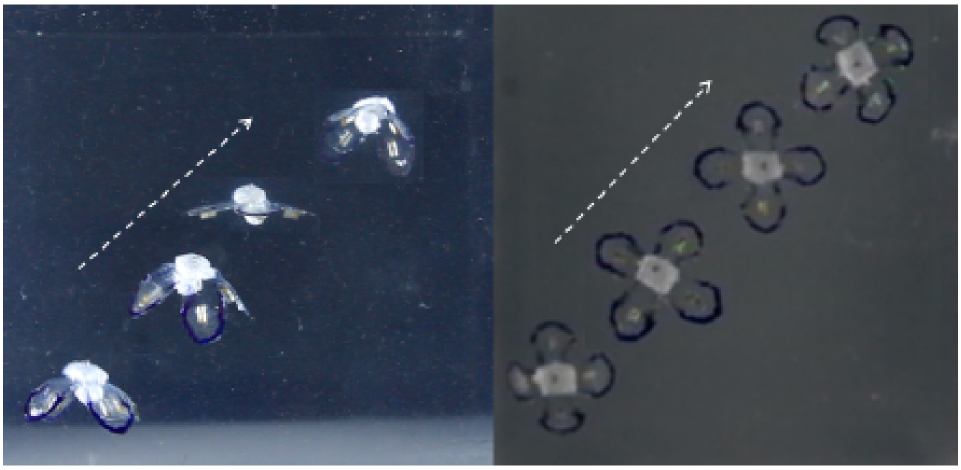

Figure 11: The illustration of microrobot's locomotion from top and side view (Ko et al., 2012).

field was applied to compensate for this power wire issue (Ko et al., 2012).

A hybrid microbot was designed by Zeeshan et al. made of ferromagnetic alloy head and a helical polymer tail that are attached together with the rigid connection as shown in the picture (Zeeshan et al., 2013). This design is lighter than the fully magnetic microdevice and improves navigation by reducing sedimentation. Furthermore, electrodepositing applied as part of fabrication method besides photolithography results in biocompatibility of the micro device. The proposed model showed physical stability in the liquid environment (Zeeshan et al., 2013).

3 Project Plan

For the purpose of this project the different proposed models of helical microrobots were studied and analysed in order to reproduce the helical microswimmers. The aim is to get the advantages of each model to improve the efficiency, power, motion velocity and cost-efficiency for mass production of the microswimmers. The fabrication of microswimmers will be by Nanoscribe facility using 3D laser lithography. After the microrobots are produced their characteristic and performance will be analysed under the scanning electron microscope.

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