IMAGE-BASED MAGNETIC CONTROL OF SELF-PROPELLING CATALYTIC MICRO MOTORS

J. de Vries[1], J. Keuning[2], L. Zondervan[1], S. Misra[2] and L. Abelmann[1]

[1]*MESA+ Institute for Nanotechnology*
[2]*MIRA Institute for Biomedical Technology and Technical Medicine*
University of Twente, Enschede, Netherlands

***Abstract* — This paper describes our work to magnetically steer self-propelled devices which move by catalysis of hydrogen peroxide. We demonstrate manipulation of paramagnetic particles with a diameter of** $100\,\mu\mathrm{m}$ **to a given setpoint by means of magnetic field gradients, as well as self-propelled movement of gold-platinum rods. We discuss how to reach magnetic torque control of catalytic micro motors.**

***Keywords:* Gold/platinum, self-propelling, micro motors, hydrogen peroxide**

I – Introduction

For many decades people have been working on downscaling the size of machines. The most famous prediction of micro- and nano-scaled machines is probably the lecture of Richard P. Feynman titled "There is plenty of room at the bottom" which he gave on December 29$^{\text{th}}$ 1959. Here Feynman described among other things tiny machines that could manipulate the micro- and nano-sized world [1].

One of the biggest problems with such a micro- or nano-sized device is to find a way to power it and to make sure it can be 'refueled' once the power of machine runs out. A solution to this problem is a device that can draw power from its environment. This way the small particle does not have to carry its own power source and 'fuel' can be added to the environment in order to make the device work.

Research has been performed into devices which can move by catalyzing a reaction in a liquid environment [2]. An example of such a reaction is a piece of platinum put into a solution of aqueous hydrogen peroxide. Inside the peroxide the platinum can catalyze a reaction to separate hydrogen peroxide into water and oxygen by the following reaction:

$$2\mathrm{H_2O_2} \rightarrow 2\mathrm{H_2O} + \mathrm{O_2}.$$

When using only platinum, the device will stay in place. But several groups have successfully created moving devices or 'microswimmers' from gold/platinum rods [3, 2]. One of the principles of movement reported is that the platinum part of the rod catalyses the reaction mentioned above to create oxygen. The oxygen forms into bubbles within the liquid until they reach a critical size. When the critical size is reached the bubble explodes and thrusts the particle in the direction of the gold part as schematically shown in figure 1 [2].

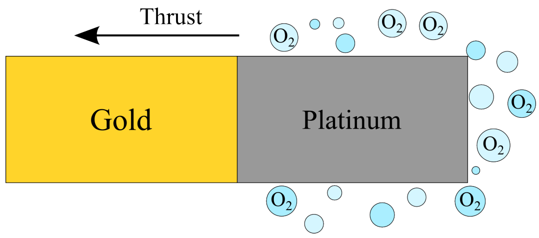


Figure 1: *Schematic view of a gold and platinum rod where the platinum side catalyses the hydrogen peroxide and oxygen bubbles are formed*

Although the self-propelling particles can move through the liquid without external influence, the direction of movement needs to be controlled from the outside world. Since we do not want to add extra mass or volume in the form of electronics or actuators to the device, we choose to add a magnetic part to the particle in order to steer the particles with an external magnetic field. In this paper we discuss our first findings to create such a micro motor and our capabilities to steer micro-sized particles.

II – Magnetic setup

To be able to manipulate the self-propelling micro motors a setup was build which consists of four coils centered around a liquid container with a volume of $10\,\mathrm{mm} \times 10\,\mathrm{mm} \times 2\,\mathrm{mm}$. The particles in the container are imaged by a Sony XCD-X710 1024×768 pixels FireWire camera which is mounted on a Mitutoyo FS70 microscope unit with a Mitutoyo M Plan Apo 2× / 0.055 Objective. The camera is connected to a computer running a program that can track the particles and adjust the magnetic field generated by the coil system. Two software programmed proportional-integral (PI) controllers adjust the current through the coils to steer the particles to the desired location in the camera image shown in figure 2 [4].

The magnetic field supplied by the coils was calculated by means of a finite element model (FEM) [5]. Each coil is represented by a hollow cylinder with a current density corresponding to a current of 1 A running through a coil with approximately 1680 turns. A top down view of the four coil set can be seen in figure 3(a) where a current is applied to the top coil. The variation in color from blue to red shows the strength of the normalized magnetic field, the arrows show its direction. Figure 3(b) shows the y-component of the magnetic field over the length of the liquid container. The field strength in the center of the container is

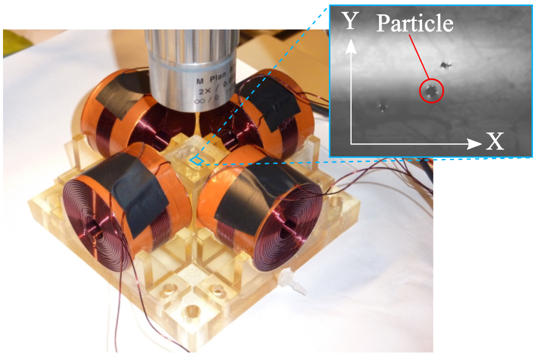


Figure 2: *Image of the magnetic setup with the four coils and the microscope. The inset shows the camera picture with a small cluster of particles*

approximately $3\,\mathrm{kA\,m^{-1}}$.

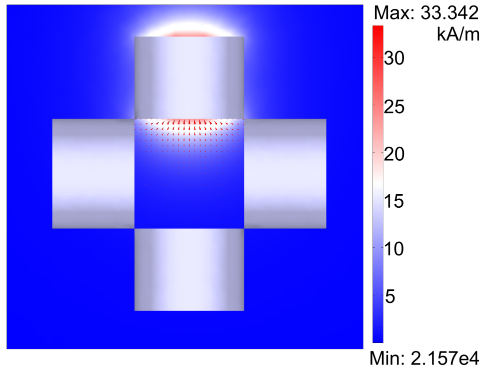
For the initial test paramagnetic particles are used which consist of iron-oxide in a poly(lactic-acid) matrix with a diameter of approximately $100\,\mu\mathrm{m}$. The magnetic moment of each particle makes it possible to drag it through the liquid using a magnetic field. This occurs when the force applied by the magnetic field overcomes the drag force created by the particle moving through the liquid. The PI control positions the particle with an accuracy of $7\,\mu\mathrm{m}$ from the setpoint. The maximum attained speed of the paramagnetic spheres was determined to be $235\,\mu\mathrm{m\,s^{-1}}$ [4].

In figure 4 a screen shot of the particle tracker program is shown with a smaller cluster of particles which are manipulated. The green square indicates the region of interest where the particle that is manipulated is located. The pink lines give the direction of the position vectors (*x*- and *y*-directions) as outputted by the controller.

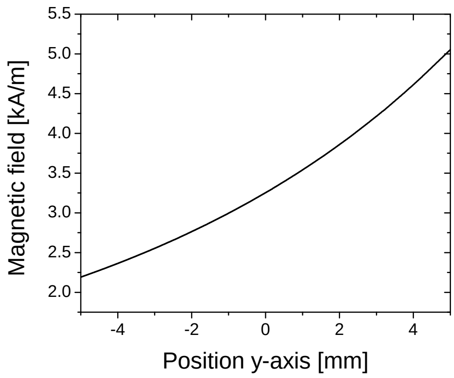
The setup enables steering of the particles through the liquid on predefined trajectories with setpoints. When the particle is within approximately $23\,\mu\mathrm{m}$ (10 pixels) from its current setpoint, the next setpoint is given to the controller. As an example, we created a series of setpoints describing a 'figure 8' trajectory. Figure 5 shows the setpoints given to the controller by red circles and the resulting trajectory of the particle cluster by the blue line. As can be seen the cluster of particles closely follows the given setpoints. The speed of the particle cluster was around $122\,\mu\mathrm{m\,s^{-1}}$. The control algorithm was not yet optimized, and higher speeds are certainly possible.

III – Self-propelled particles

To drag the particles through the liquid we applied relatively high fields up to $3\,\mathrm{kA\,m^{-1}}$ because all energy required to move the particle needed to be supplied by the magnetic field. To decrease the required magnetic field we only want to manipulate the direction of movement of the particles in the liquid and use a different source of energy to move the particle. One such possibility is to submerge the particle in its own



(a) Magnetic field produced by a single coil



(b) The *y*-component of the magnetic field produced by a single coil in the liquid container

Figure 3: *Finite element simulation of coil set used for magnetic steering*

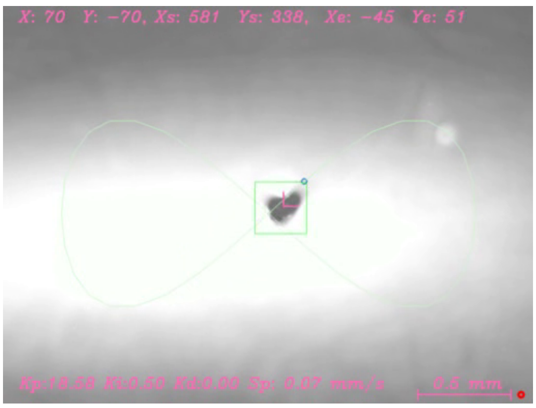


Figure 4: *Screenshot of the particle tracking program where the green square indicates the particles that is manipulated and the pink lines represent the x- and y-position vectors given by the controller output.*

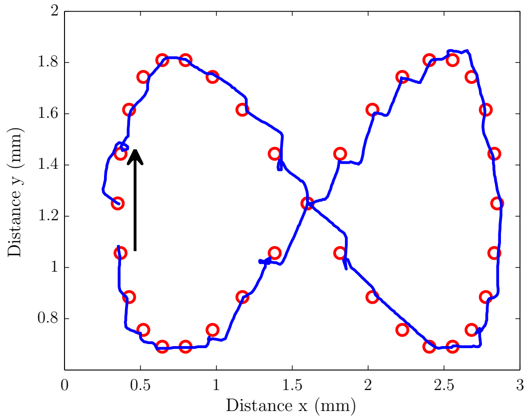


Figure 5: *Comparison the setpoints given to the control software (red dots) and the path of the particles cluster (blue line)*

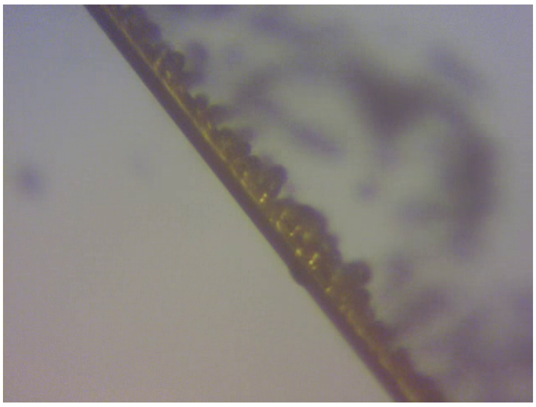


Figure 6: *Piece of gold bondwire with a layer of sputtered platinum in hydrogen peroxide solution where only bubbles are formed on the platinum side*

fuel, much like bacteria. Hydrogen peroxide is one of the simplest systems available, but we imagine future applications of micro-robots in blood streams.

For our first attempt to make a movable 'motor' from gold and platinum we sputtered an approximately 500 nm platinum thin film on a small thread of gold bondwire with a diameter of 50 µm . When the coated gold wire is submerged into a hydrogen peroxide solution bubbles are formed at the platinum surface as can be seen in figure 6. To verify that only the platinum acts as a catalyst a bare piece of gold bond wire is put into the peroxide solution. Indeed, there was no reaction as can be seen in figure 7.

When the platinum surface area is sufficiently large, bubbles will be formed which grow until they leave the wire. The recoil will propel the micro motor in the opposite direction. When a small piece of the platinum/gold wire was put into the hydrogen peroxide solution, movement could be seen from the particle in the setup. There was irregular movement in the path of the particle which was most likely caused by mechanical vibrations of the table and brownian motion due to heating of the liquid by the microscope light source.

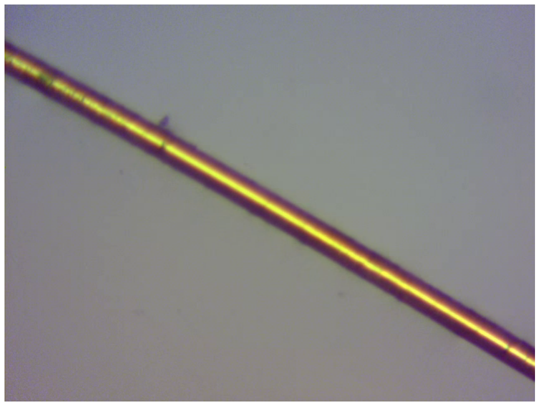


Figure 7: *Piece of bare gold wire in hydrogen peroxide solution where no bubbles are formed on the surface*

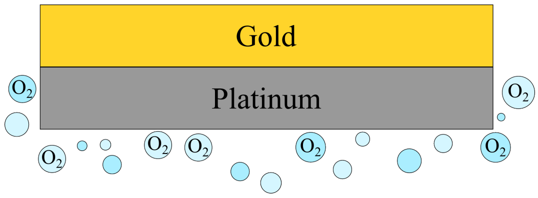


Figure 8: *Schematic view of the gold wire coated by platinum where only bubbles are formed on the platinum surface*

The result can be seen in figure 9. Here three subsequent frames are shown where the particle can be seen moving relative to the surface of the water container.

For such a 'bubble propulsion' mechanism to work it is important to have a suitable shape to decrease fluid drag. The drag force is proportional to the area of the particle perpendicular to the direction of movement. A large surface area thus results in a large drag on the micro motor and inhibits movement. In our first attempt the gold wire was covered with platinum on the side instead of the end as shown schematically in figure 8, which decreases the ability of the micro motor to move.

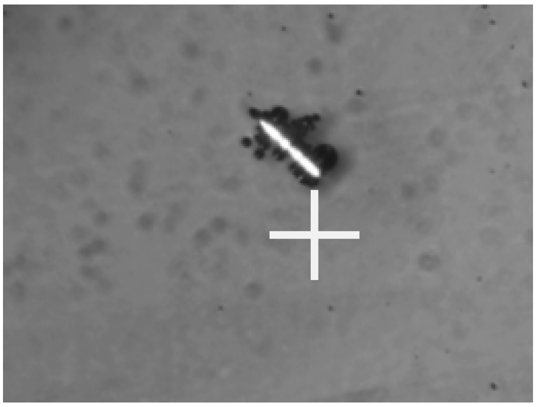
IV – Conclusion

We have shown that we can manipulate the position of paramagnetic particles with a diameter of 100 µm with an accuracy of 7 µm from a desired setpoint using a magnetic setup. A setup of two proportional integral control loops makes it possible to drag the particles through the liquid to a given position or along a given trajectory.

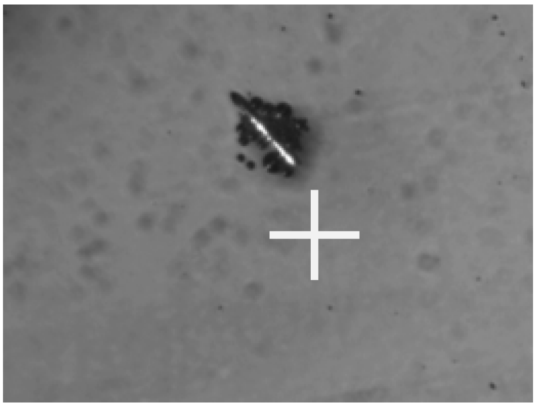
A gold wire was coated with platinum using a sputtercoater to create a self-propelled micro motor. When a small part with a length of approximately 300 µm of the gold/platinum wire was put into hydrogen peroxide solution a large number of bubbles were formed and the wire moved through the liquid. Due to the large number of bubbles formed on the surface it was not possible to see whether the wire actually moved in the direction of gold side as expected. The fluid drag is proportional to the area of the wire perpendicular to the direction of movement therefore the shape shown schematically in figure 1 would be more suitable than the shape shown in figure 8 for linear movement.

V – Future work

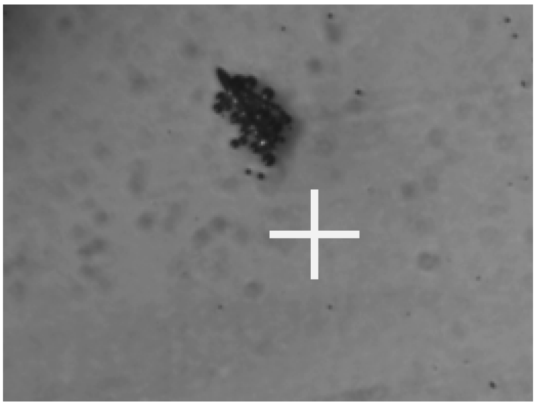
Our next step is to create a small rod of gold and platinum where the tip of the rod is coated with platinum. Due to the decreased area of the wire perpendicular to the direction of movement, we expect this shape to be more beneficial for linear movement then the side coated gold wire. The use of an additional magnetic layer should enable control of the direction of movement of this rod by applying a magnetic torque. In this way we separate control and propulsion, so the required external magnetic field can be considerably smaller.



(a) Frame 1



(b) Frame 2



(c) Frame 3

Figure 9: *Three subsequent camera frames showing the movement of the gold/platinum rod in hydrogen peroxide solution. The cross has the same position in each frame and acts as a reference*

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