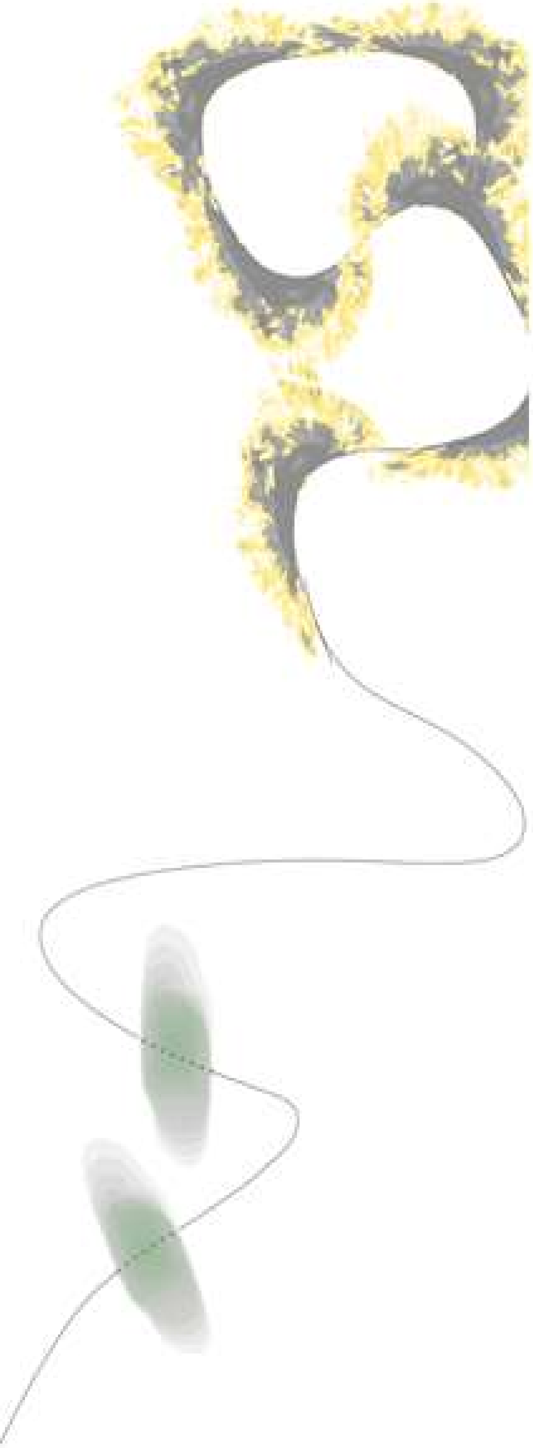
BACHELOR THESIS



Simulating and testing of the movement of a millirobot influenced by a static magnetic field.

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1 Introduction

1.1 Motivation assignment

There are numerous applications for millirobots in the medical field (1–5), for instance the ability of localized delivery of substance like chemicals (1,2) or to use the millirobot for diagnosis by sample collections (1,2). There are many more uses for the millirobot for instance in endoscopy (3) and sensing specific points in the body(1),(2) There is a lot of research in the use of millirobots for the medical field. Since the use of a millirobot would negate the need for an invasive surgery or provides a service that otherwise would not be possible. However, there are certain problems with millirobots such as the difficult task of down-scaling of all the necessary technology. Since the millirobot needs to be as small as possible in order for it to be used inside of the blood vessel of a patient. The sub-millimetre scale of the millirobot makes it very difficult for the millirobot to do complex tasks. Because on that small scale adding complex components like sensors or chips is not an option. Down-scaling those components to sub-millimetre scale is extremely difficult. So in order to keep the scale of the millirobot as small as possible the components will need to be simple. Which in turn means that the components used to carry out the millirobots possible function cannot be complex. Meaning that the tasks the millirobot can carry out will have to be simple. Furthermore this also means that the methods of locomotion of the millirobot also needs to be simple.

1.2 Aim of the assignment

The aim of this assignment is to provide a proof of concept of locomotion of a millirobot influenced by a static magnetic field. This assignment focuses primarily on the movement of the millirobot by the use of the tri axial coils. With the aim of answering the research question. 'Is it possible to create enough torque to make a device in a fluid rotate. By use of coils onboard the device that are influenced by a static magnetic field'. Where the movement of the rotation is controlled by having a time varying current go through the coils causing the production of magnetic moments to also vary with time. With this alternate production of magnetic moments a torque can be produced with the help of a static magnetic field leading to the rotation of the device. The tri-axial coil system seen in figure 1 is used so that the movement can happen three Dimensions. This tri axial system should not use any complex components which should keep the scale of the millirobot down. The assignment will first model the movement with the use of simulations to see the effects of the tri axial coils on the movement and to see how the movement can be controlled. Then the magnetic moment of the coils will be tested to measure if the torque provided by the coils is possible in practice. The assignment continues on the article 'Scaling rules for micro-robots with full energetic autonomy' (6) and aims to fill the gap between the theoretical framework of the millirobot dynamics and the practical constraints of electrical engineering. With the end goal to see if the theoretical framework of the millirobot will be possible in practice by modelling and testing of individual parts of the millirobot movements.

2 Background information

To understand how the model works and why the experiment is done first some background information about the dynamics and kinematics needs to be explained.

2.1 Governing dynamics

The dynamics that influence a robot on macro scale and micro scale are the same however the magnitude of the influence of each dynamic changes depending on the scale(7). This means that in order to know the governing dynamics of a micro robot certain assumptions can be made and some effects are negligible (7).

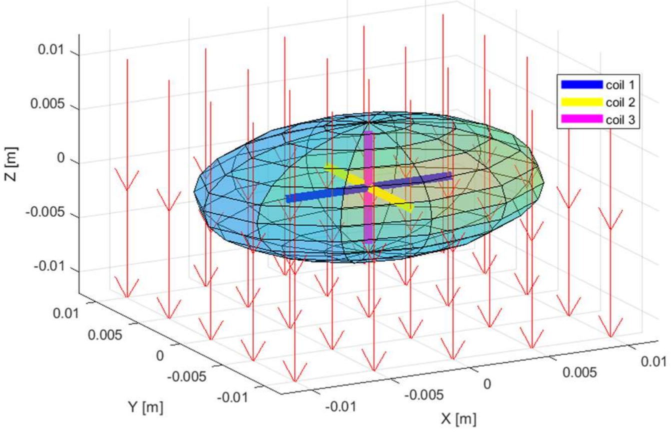


Figure 1: illustration of the layout of the capsule in relation to the magnetic field. The X,Y,Z axis represent the global frame of reference while the yellow, blue, magenta represent the x,y,z axis of the local frame. The coils of the device are orientated along each local axis.

The tri axial coils create a magnetic torque in order to rotate the robot. The robot undergoes drag torque when it rotates the drag torque and magnetic torque can be used to make a torque balance (8) as follows.

$$\tau_m + \tau_d = I\alpha \ eq\ 1\ (8)$$

With $\tau_m = m \times B$ *where* $m = N\,S\,I$ *for a coil and* $\tau_d = 8\pi r^3 \eta \omega$ *where m= magnetic torque* $B =$ *static magnetic field ,*$r =$ *radius of the robot* $\eta =$ *fluid kinematic velocity,* $\omega =$ *rotational velocity (8)*

Because of the low Reynolds that micro robots experience the inertia term can be neglected (8) this means the term Iα can be set at 0. This makes it possible to rewrite equation($\tau m + \tau_d = I\alpha$ eq 1 (8) *) into the formula for rotational velocity (8) as follows:*

$$\Omega = \frac{m \times B}{8\pi r^3 \eta} \ eq\ 2\ \ (8)$$

With this formula for the rotational velocity the movement caused by an coil influenced by an magnetic field can be calculated. Which will be used in the model in order to model the coils.

2.1.1 Biot savart law

The biot-savart law will have to be used to derive the magnetic moment produced by a coil while measuring the magnetic field. The Biot savart law can be rewritten[insert book citation of magnetic fields] in order to get an equation to calculate the magnetic dipole moment from which the magnetic moment can be determined

$$B(r) = \frac{\mu_0 I}{4\pi} \int \frac{dI(r - r')}{||r - r'||^3} \ eq\ 3$$

$$B = \frac{\mu_0 m}{2\pi ||z||^3} \ eq\ 4$$

$$m = \frac{2\pi ||z||^3 B}{\mu_0} \ eq\ 5$$

$$m = NI\pi R^2 z \ eq\ 6$$

With the above equations *(3,4,5) the magnetic moment of a coil can be calculated equation 6. This will be used during the experiment in* order to test if the required magnetic moment for movement can be obtained.

2.2 Governing kinematics

In order to accurately model the movement the movement of the robot two axis systems was used(8). One of the axis system does not rotate with the body and instead does not move. The other axis system does rotate with the body (8). However both of the origins of the axis system are in the middle of the robot. In order to model the movement it is needed to convert coordinates of one axis system to the other this is done by the use of rotation matrices seen as follows.

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x \\ 0 & \sin\theta_x & \cos\theta_x \end{bmatrix} \text{ eq 7}$$

$$R_x = \begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y \\ 0 & 1 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y \end{bmatrix} \text{ eq 8}$$

$$R_x = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 \\ \sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ eq 9}$$

The matrices in equations(7,8,9) are used to transform the x,y,z coordinates of the axis system that moves with the millirobot to the x,y,z coordinates of the axis system that does not move. Where each matrix is used for a different axis of rotation. With equation(7) for rotation around the x axis, equation(8) for rotation around the Y axis and equation(9) for rotation around z axis

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = R_z R_y R_x \begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} \text{ eq 10}$$

equations(7,8,9) can be combined to make equation(10) which transforms the coordinate's to the different axis system for all the rotations around the axis systems.

2.3 Behavior of a coil effected by a magnetic field

The torque that an individual coil can provide is heavily dependent on its orientation in relation to the magnetic field. Furthermore the direction in which this torque is applied is also dependent on the orientation.

2.3.1 Magnitude of the torque

The sum of the magnetic moments of the coil in the x,y and z direction will always be equal to $N * S * I$. However the torque that will be generated decreases the more the coil's orientation aligns with the magnetic field. As can be seen from simulation results seen in figure 2 Where it can be seen that the velocity decreases as the coil is more aligned with the magnetic field. important to note is that the decrease in torque happens when the magnetic moment lines up with the magnetic field but also when it is in the opposite direction as the magnetic field. This means that the forces provided by the coils will not be constant and depends on the orientation of the robot. These factors will have to be taken into account when attempting to control the movement.

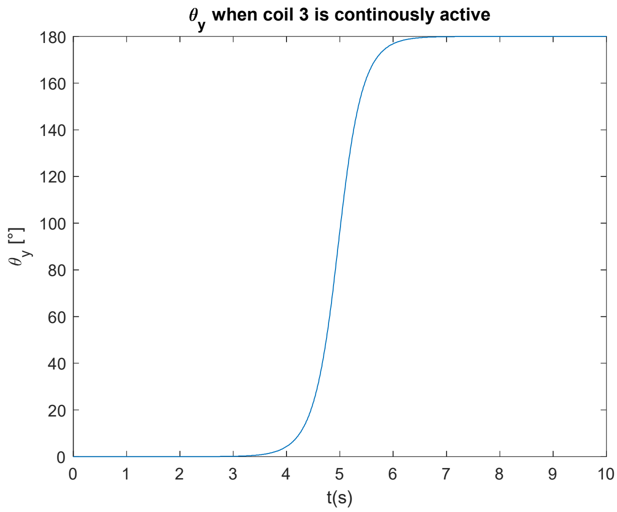


Figure 2: Continuous activation of coil 3 where it can be seen that when the coil aligns more with the magnetic field the rotational velocity decreases.

2.3.2 Direction of the torque

The direction of the torque depends on the orientation of the coil. As seen in Figure 3: figure showing how with different orientation the direction of the torque will change. Where it can be seen that the torque of a coil will always try to align with the magnetic field illustrated here as the red lines .since the angle between the magnetic moment of each coils differs. This causes the torque's produced by each coil to rotate each coil in a different direction.the direction of the torque can switch depending on its alignment with the magnetic field. This is important for the control of the movement since the coils should not be activated when the direction of the torque is switched in order to not have rotation in the wrong way.

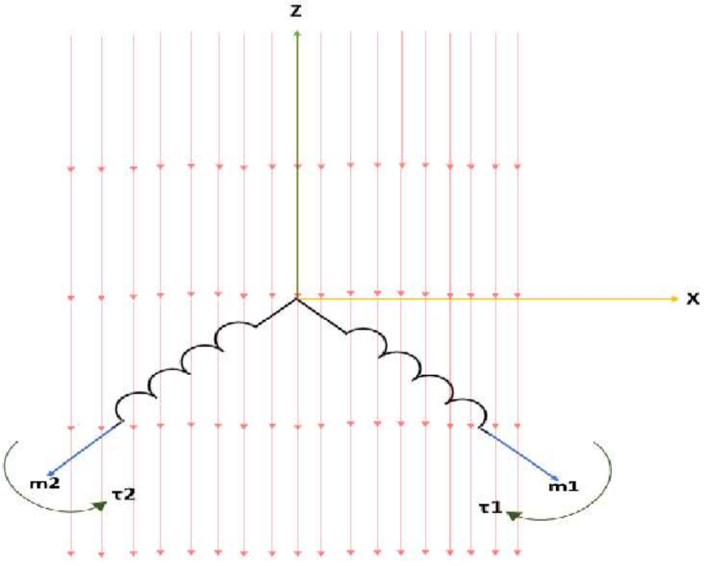


Figure 3: figure showing how with different orientation the direction of the torque will change. Where it can be seen that the torque of a coil will always try to align with the magnetic field illustrated here as the red lines .since the angle between the magnetic moment of each coils differs. This causes the torque's produced by each coil to rotate each coil in a different direction.

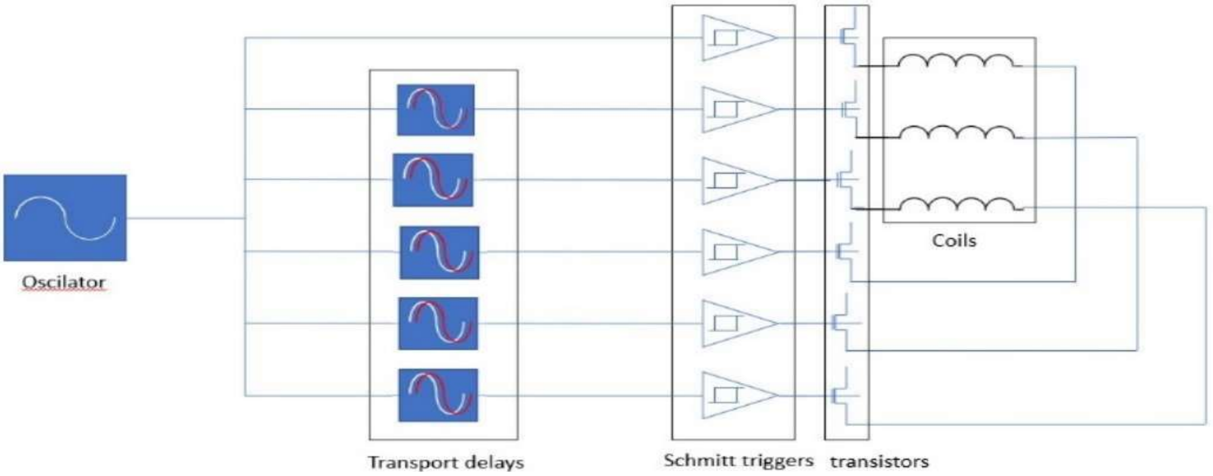


Figure 4: Diagram based on the electrical circuit provide by slam Khalill

3 Diagram analysis

3.1 Function of the system

The system illustrated in the Diagram in Figure 4 is used to alternate the activation of the coils in order to create the dipole moment that creates the magnetic torque needed to rotate the device. This system also only needs one signal in order to power three coils which makes the use of one power source possible. Below is the explanation of the individual components and their function in the system.

3.2 Purpose of the individual components

3.2.1 Oscillator

The purpose of the oscillator is to convert the electric current from direct current (DC) to alternating current(AC). With an AC signal the signal is in the form of a sinusoid[B3]. This property of the signal will be used to create the alternate activation of the coils that are needed for the movement.

3.2.2 Schmitt triggers

Because of the noise that will be amplified by the amplifier there is a need for filtering the signal this will be done by the smith trigger. The signal will need to go above a certain activation value before the smith trigger sends it's signal. What makes a smith trigger different from a normal comparator is that the signal needs to drop below a lower value than the activation value is in order to stop sending it's signal. This helps filtering the noise and makes sure that the signal will not have interruptions.

3.2.3 Transistor

The transistor in this diagram is used as an on/off switch for the activation of the coils. When the smith triggers are activated it will send it's signal to the base of the transistor allowing the outside current to run through the coils. And when the smith trigger is not activated there will not be a current to the base making it so that the current cannot go through the transistor and de coil is deactivated.

3.2.4 Phase shifter

The phase shifters are used to delay the signal of the oscillator in order to make the coils activate at different times to make the device rotate. Due to the Schmitt trigger the signal will only go to the coils when the activation value is reached which will happen only around the peak. And due to the sinusoidal way of the signal, the signal has a different phase the peaks will be at a different time. This will cause the activation of one of the coils to be at a different time than the other coils.

3.2.5 Coils

If a current moves through a coil a dipole moment is made which with the help of the static magnetic field that makes an magnetic torque. This torque is used to make the device rotate due to the static magnetic field. However a coil will only produce torque when it's not aligned with the static magnetic field. One coil will only rotate as far as it needs to align itself with the static magnetic field. This is the reason that multiple coils that alternate their activation are needed. Multiple coils are needed to make sure that there is always an coil positioned so that it creates a magnetic torque. Furthermore the alternating activation is needed so that the coils don't produce counter acting torque's causing the rotation to slow down or stop completely.

4 Simulation of the diagram

4.1 Function of the system

Based on the diagram provided by Khalil Islam a simulation was made in Simulink as seen in Figure 5. This simulation takes as input signal the voltage that goes through the oscillator here shown as a sine signal. It also has a input of an outside current that will go through the transistor an trough the coil leading to the magnetic moment. The output of the system is the angle of the (x,y,z) axis in the middle of the sphere in reference to its beginning position. This simulation is used to see what each individual components influence will be on the rotation of the sphere in order to find the best possible components for the design.

4.2 Simulation of individual components of the diagram

4.2.1 Oscillator

The oscillator is represented in the simulation as a signal source in the form of a sine wave. This is to simulate an AC signal that will come from an oscillator. The simulation does not take in account the effects of an oscillator on the output signal like a voltage drop or current drop this will have to be tested in the lab to get accurate results. The noise is added in the simulation since the Schmitt trigger is implemented to filter the noise. So in order to test the effectiveness of the triggers there needs to be noise added.

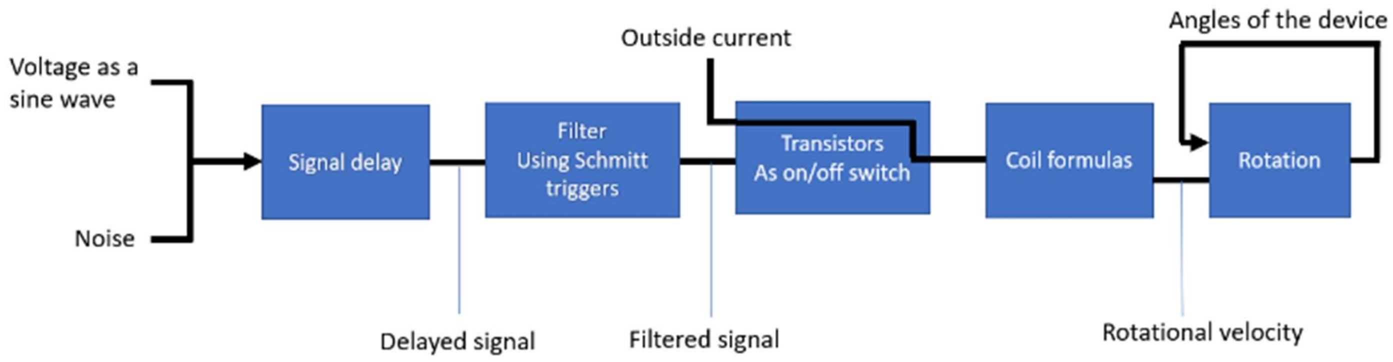


Figure 5: Simulink simulation of the diagram provided by Islam, Khalil

4.2.2 Phase delays

The phase delays are represented as transport delays in the circuit. Like the oscillators the effects of the phase delays of the signal are unknown and will have to be researched in the lab.

4.2.3 Schmitt triggers

The Schmitt triggers work the same in the simulation as in real life since simulink has a function that is similar as a schmitt trigger. The only thing that needs to be done is picking the values for the trigger based on real life products.

4.2.4 Transistors

The transistors are used as an on off switch in the diagram so in the simulation they are represented as a switch that switches on at a specific value. These switches will turn on if a specific value is reached and send trough the outside current emulating the transistor used in the diagram.

4.2.5 Coils

The initial configuration of the coils can be seen in figure 1. where coil 1 aligns with the x axis coil 2 with the y axis and coil 3 with the z axis. Furthermore the origin of the axis system is also the middle point of the robot.

The formulas used to simulate the coils are in a Matlab function block. The formulas used are the magnetic moment of a coil and the rotational velocity of a sphere influenced by magnetic torque[B2] as seen in the part governing dynamics. These formulas are used to get the rotational velocity along each axis with these rotations the velocity is converted to angles using the movement block. In the movement block the velocity is multiplied by the time step and added to the old angle creating the new angle causing the modelling of the movement.

4.2.6 Animation

The output of the Simulink model is the movement. However this will need to be converted to the static axis system in order to properly model the movement of the robot. This is done in an outside MATLAB script that uses these new coordinates to make an animation of the movement to better visualise what is happening.

5 Results simulation

In order to check if the simulation was working correctly certain variables of the simulation where varied in order to check if the model has a correct response. The variables that have been varied are the surface of the coils, the number of turns of the coils, the current trough the coils, the viscosity of the fluid, the magnitude of the static magnetic field, the radius of the sphere and the frequency of the input signal. The variables where tested with three different values with a spacing of a multiple of 10 between each step in order to better see the effect of each variable.

5.1 Standard values of the simulation

Table 1 includes the values of the when they are not the one being varied. So these values will be constant throughout the testing unless indicated otherwise. The result of the simulation with these standard values can be seen in Figure 6.

Table 1: Standard simulation values

S	$surface\ area\ of\ the\ coil$	$0.007m^2$
N	$number\ of\ turns\ of\ the\ coil$	160
I	$current\ trough\ the\ coil$	$0.020\ A$
η	$viscosity\ of\ fluid$	$1\ cP$
B	$magnitude\ of\ magnetic\ field$	$[0\ 0\ \ -0.013]\ T$
R	$radius\ of\ the\ sphere$	$0.015\ m$
f	$frequency\ of\ input\ signal$	$1\ Hz$

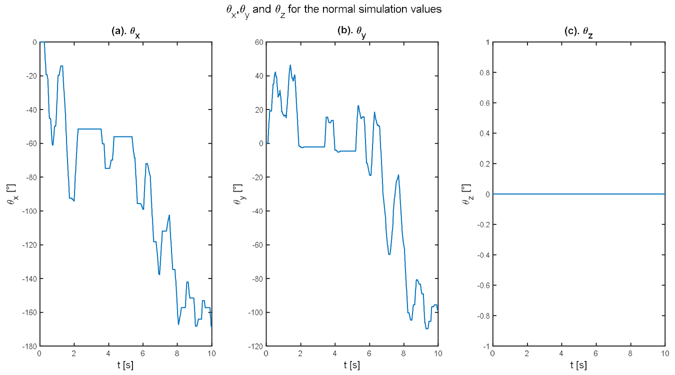


Figure 6: Results of the simulation of angle θ_x , θ_y and θ_z of the robot with the standard simulation values. Where the rotation of the device around the x axis over time is shown. (a) Simulation of θ_x where it can be seen that the angle θ_x decreases over time with some interruptions in the opposite direction. (b) simulation of θ_y where it can be seen that the angle θ_y decreases over time with some interruptions in the opposite direction. (c) Simulation of θ_z where it can be seen that there is no rotation.

5.2 Results of varying the variables

5.2.1 Magnetic moment of the coils

From the magnetic moment simulations in Figure 7,8 it can be seen that the rotational velocity increases when the magnetic moment increases compared to figure 6. This is consistent with the expectation that increasing the magnetic moment . What is also interesting is that with more magnetic torque the device has a clearer rotation in the negative x angle with less of a positive angle velocity and with the y angle the angle oscillates around zero.

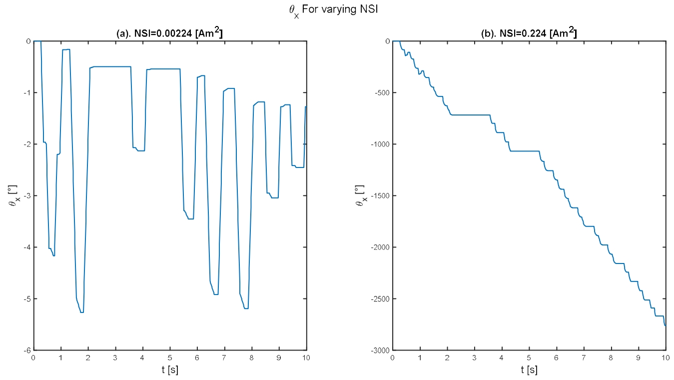


Figure 7: Results of the simulation of angle θ_x of the robot over varying S. Where the rotation of the device around the x axis over time is shown. (a) simulation with $S = 0.0007\ m^2$where it can be seen that the angle θ_x oscillates around -2 degrees. (b) simulation with $S = 0.07\ m^2$where it can be seen that the angle θ_x decreases over time with minimal interruptions in the opposite direction.

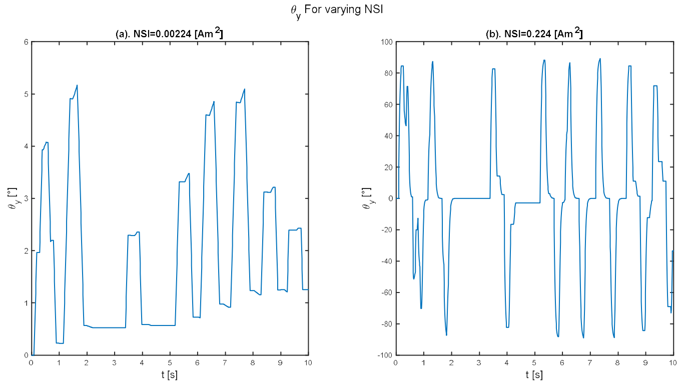


Figure 8: results of the simulation of angle θ_y of the robot over varying S. Where the rotation of the device around the y axis over time is shown. (a) simulation with $S = 0.0007\ m^2$where it can be seen that the angle θ_y oscillates around 2 degrees. (b) simulation with $S = 0.07\ m^2$where it can be seen that the angle θ_x has big oscillations around 0 degrees.

5.2.4 Viscosity of the fluid

When the viscosity increases the velocity of the robot decreases compared to the normal results as seen in Figure 9,10 this is in line with the expectations that the formula gives us. What is also noticeable is that with angle x with the increase of viscosity there is also an increase in oscillations. Whereas with the y angle it starts with oscillating then has a smoother line. However when the viscosity increases the y angle starts oscillating again.

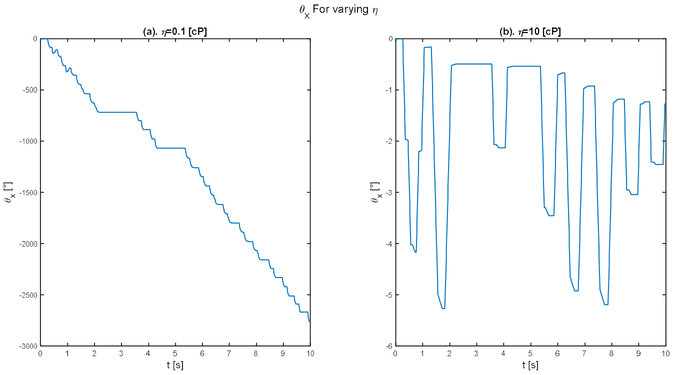


Figure 9: results of the simulation of angle θ_x of the robot over varying η. Where the rotation of the device around the x axis over time is shown. (a) simulation with η =0.1 cP where it can be seen that the angle θ_x decreases over time with minimal interruptions in the opposite direction. (b) simulation with η =10 cP where it can be seen that the angle θ_x has big oscillations around -2 degrees.

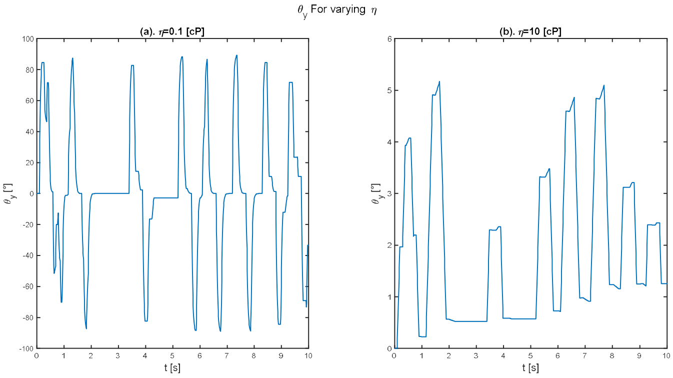


Figure 10: results of the simulation of angle θ_y of the robot over varying η. Where the rotation of the device around the y axis over time is shown. (a) simulation with η =0.1 cP where it can be seen that the angle θ_y decreases over time with minimal interruptions in the opposite direction. (b) simulation with η =10 cP where it can be seen that the angle θ_y has big oscillations around -2 degrees.

5.2.5 Magnitude of the magnetic field

The smaller the magnetic field the smaller the rotational velocity as seen by the results in Figure 11,12, this matches the expectations. And also the angle x goes down smoother with an increase in magnetic field while for angle y there is an increase in the number of oscillations and the amplitude of the oscillations until it oscillates around the zero value at the highest magnetic field.

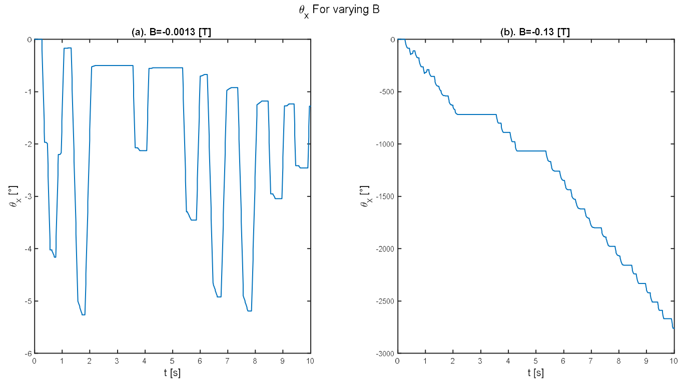


Figure 11; results of the simulation of angle θ_x of the robot over varying B. Where the rotation of the device around the x axis over time is shown. (a) simulation with $B = -0.0013\ T$ where it can be seen that the angle θ_x oscillates around -2 degrees. (b) simulation with $B = -0.13\ T$ where it can be seen that the angle θ_y decreases over time with minimal interruptions.

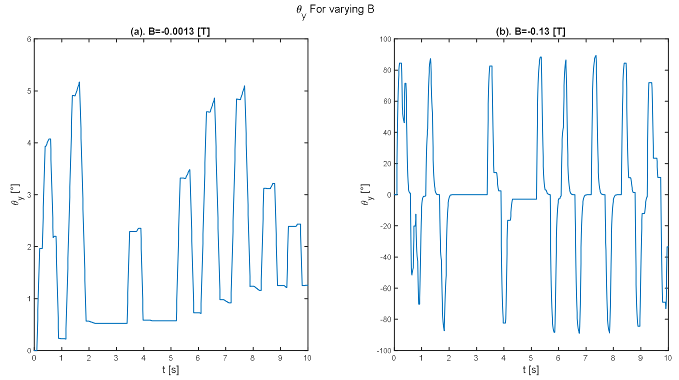


Figure 12: results of the simulation of angle θ_y of the robot over varying B. Where the rotation of the device around the y axis over time is shown. (a) simulation with $B = -0.0013\ T$ where it can be seen that the angle θ_x oscillates around 2 degrees. (b) simulation with $B = -0.13\ T$ where it can be seen that the angle θ_y has big oscillations around 0 degrees.

5.2.6 Radius of the sphere

If the sphere radius decreases the rotational velocity increases as seen in Figure 13,14 this is in line with the expectations since the magnetic field stays the same but the drag decreases due to the smaller size. What is noticeable is that with the large radius the angle makes peaks however it always returns to zero but it does not exceed. It is unknown what causes this behaviour.

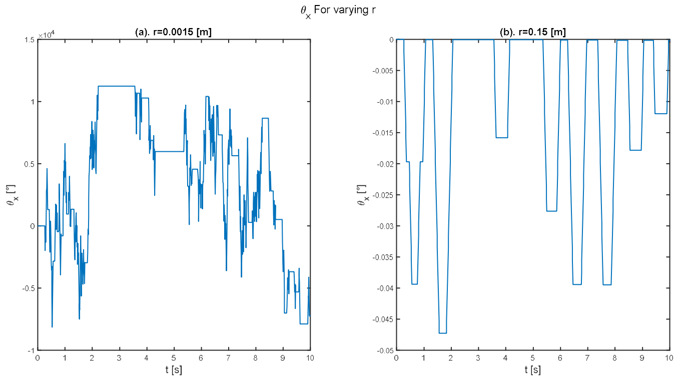


Figure 2: results of the simulation of angle θ_x of the robot over varying r. Where the rotation of the device around the x axis over time is shown. (a) simulation with $r = 0.0015\ m$ where it can be seen that the angle θ_x decreases over time with minimal interruptions.. (b) simulation with $r = 0.15\ m$ where it can be seen that the angle θ_y has very small spikes that originate from 0 degrees and are around -0.015 to -0.045 degrees.

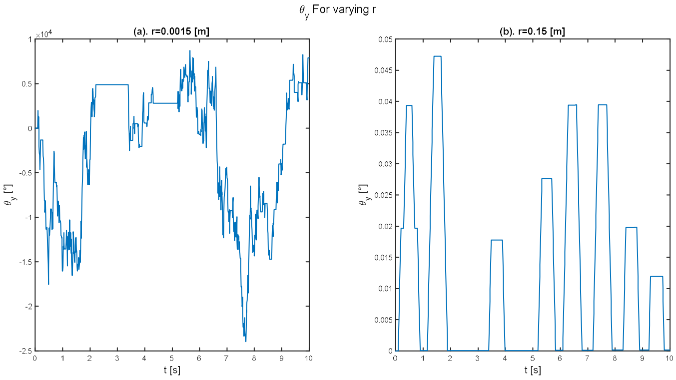


Figure 14: results of the simulation of angle θ_y of the robot over varying r. Where the rotation of the device around the y axis over time is shown. (a) simulation with $r = 0.0015\ m$ where it can be seen that the angle θ_y has large oscillations around 0 degrees.. (b) simulation with $r = 0.15\ m$ where it can be seen that the angle θ_y has very small spikes that originate from 0 degrees and are around 0.015 to 0.045 degrees.

5.2.7 Frequency of input signal

What can be seen in the simulations seen in Figure 15,16 is that with low frequency's there is less noise than with high frequency's. With the high frequency there is a lot of noise, this was also expected. Since with the low frequency the coils are active for longer, this makes the movement more smooth since the rotation takes longer which increases the chance that the coil is in the correct orientation to complete the rotation. While with the high frequency the chance that the coil is not in the correct orientation due to the low activation time is larger causing the noise as a result.

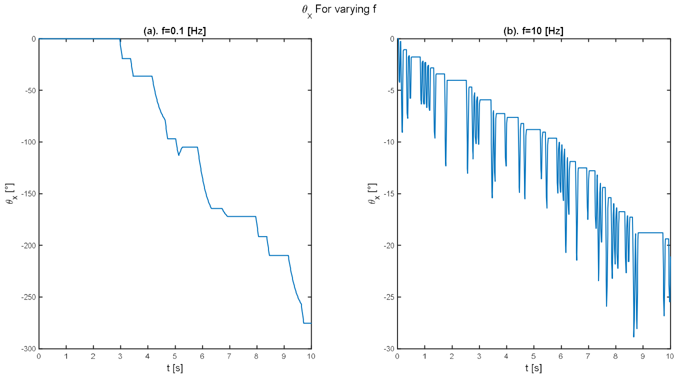


Figure 15: results of the simulation of angle θ_x of the robot over varying f. Where the rotation of the device around the x axis over time is shown. (a) simulation with $f = 0.1\ Hz$ where it can be seen that the angle θ_x decreases over time with limited interruptions. (b) simulation with $f = 10\ Hz$ where it can be seen that the angle θ_x decreases over time with a lot of spikes up and down

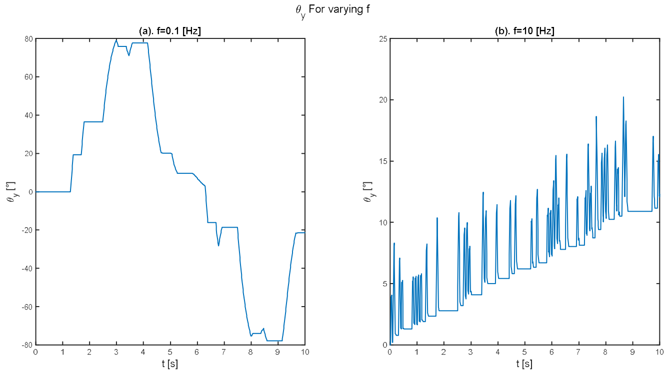


Figure 16: results of the simulation of angle θ_y of the robot over varying f. Where the rotation of the device around the y axis over time is shown. (a) simulation with $f = 0.1\ Hz$ where it can be seen that the angle θ_y has a wide pike to around 80 degrees and later has a wide peak down to around -80 degrees. (b) simulation with $f = 10\ Hz$ where it can be seen that the angle θ_y increases over time with a lot of spikes up and down

5.3 Spikes in the simulations

When the device has a high rotational velocity spikes in the plot can be observed as seen in figures 13,14,15,16.. These spikes are caused by two things one the fact that the velocity of the device is too high in relation to the timestep of the simulation see figure 13,14 and two the fact that multiple coils are activated at the same time see figure 15,16.

5.3.1 Spikes at high velocity

when the variables are so that there is a significantly high velocity and the time step is too large the coils can overshoot the point at which they align with the magnetic field. You can see this happen when the radius of the device gets reduced in figure 13,14. The reason it only happens when the radius is reduced Is because the radius influences the movement with a factor of 3 see equation 2 while the rest of the variables only influence the movement linearly. Therefore the other variables don't cause the rotation velocity to become to high and cause overshoot. Because of the overshoot the coil will not stop producing a moment causing the movement to continue. Furthermore as explained in section 2.3.2 the direction of the moment produced by the coil depends on the coils orientation and since the coil tries to align with the magnetic field it will cause the device to have spikes that go up and down trying to align itself with the magnetic field but it will never align because it keeps overshooting.

5.3.1.1 Changing the timestep

if the timestep is decreased so that the coil can't overshoot the point at which it aligns with the magnetic field the spikes in figure 13,14 will disappear as seen in figure 17,18. If figure 17,18 are compared *to figure 13,14 it can be seen that instead of spikes the rotation will go to a certain point and stop rotating until a new coil is activated. Meaning that the coils align with the magnetic field and stop producing magnetic moment which causes the movement to stop.*

The size of the timestep needed to give an accurate simulation depends on the magnitude of the velocity of the device. Since the velocity depends on the orientation of the coil it is difficult to predict what the correct timestep needs to be but you can make a estimation by calculating the maximum moment and seeing if in one timestep it can overshoot the alignment point. This method is however an estimation so doesn't guarantee a correct timestep.

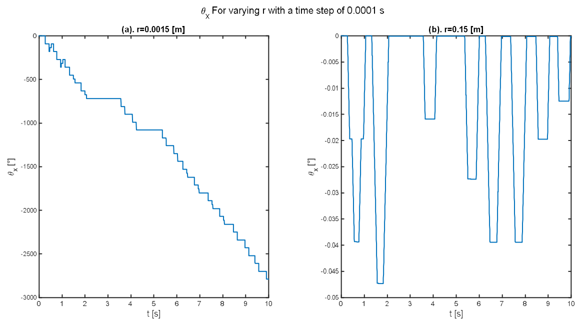


Figure 17: results of the simulation of angle θ_x of the robot over varying r with a timestep of 0.0001 s. Where the rotation of the device around the y axis over time is shown. (a) simulation with $r = 0.0015\ m$ where it can be seen that the angle θ_x decreases over time with minimal interruptions in the opposite direction (b) simulation with $r = 0.15\ m$ where it can be seen that the angle θ_x has very small spikes that originate from 0 degrees and are around -0.015 to -0.045 degrees.

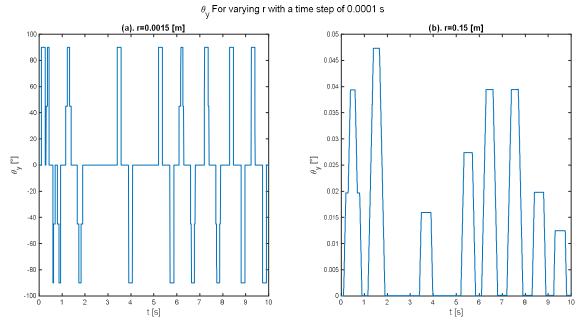


Figure 18: results of the simulation of angle θ_y of the robot over varying f. Where the rotation of the device around the y axis over time is shown. (a) simulation with $r = 0.0015\ m$ where it can be seen that the angle θ_y has big oscillations around 0 degrees.. (b) simulation with $r = 0.15\ m$ where it can be seen that the angle θ_y has very small spikes that originate from 0 degrees and are around 0.015 to 0.045 degrees.

5.3.2 Spikes with activation of different coils

The spikes in figure 15,16 are caused by the fact that the coils activate shortly after each other. Meaning that the coils are activated before the orientation of the coils is correct. Since the coils don't have enough time to rotate the device far enough before the other coils are activated. Causing the coils to produce the moment in the opposite direction of the earlier movement which leads to the spikes that go up and down.

6 Control of the movement

6.1 Movement in the wrong angle

As seen in the testing of the variables if all the coils will be activated the device will not rotate around one axis but instead two axis's. Because one of the coils will be in the wrong orientation and provide torque in the wrong direction. This makes it difficult to control the movement because in order to counter-act the unwanted rotation and make sure the device only rotates around one axis the coils need to have a variable activation time. With the variable time the device could compensate for the rotations that are not wanted this does require the movement to be periodic in order to always need the same compensation. If the undesired rotation is not periodic and always the same the device will need sensors to measure the wrong angle in order to compensate it. However this is difficult to achieve on the small scale that the robot needs to work. In order to vary the activation over time or add sensors the complexity of the device increases and in turn so does the size of the device. This is not really an option since the device needs to be as small as possible to ensure that it can complete it's tasks.

6.2 Varying magnetic field option

Therefore another option can be used in which the device will have a constant activation time and the magnetic field is the one that will vary. This does require that the magnetic field will not be static anymore however the power of the field will not have to vary but instead the activation of the field. This means that the static magnetic field will have to be artificially made and the idea of using the earth's magnetic field (6)cannot be used.

6.2.1 Explanation varying magnetic field option

The use of a varying magnetic field is that the magnetic field can be turned off whenever the coil that causes the undesired rotation is active. With this method the device can rotate in the desired direction as seen in Figure 21. Where depending on the activation time of the magnetic field rotation around the x ,y and z axis is possible. The problem with this method is that in order for it to work you have to have the correct timing between the robot and the magnetic field and since the robot's complexity needs to be as small as possible the use of sensors isn't possible. This means that either the robot needs to be in sync with the magnetic field from the start or the timing has to be figured out whit trial and error with the use of outside imaging equipment to see if the robot is rotating correctly. Also the robot needs to be aligned correctly in order to achieve the correct angle between the coils and the magnetic field. The latter problem is however also applicable to the first idea of a robot with a static magnetic field

6.2.2 Steering of the millirobot

The method with a changing magnetic field can give the possibility to steer the robot when it is already in use. Because the orientation of the magnetic field in relation to the robot can be changed allowing the robot to rotate around a different axis as can be seen in Figure 19. Where it is shown that if the magnetic field is aligned with the x axis rotation around the z axis is possible. The ability to make adjustments means that the robot can possibly reach places that it otherwise could not. For example if the robot encounters a branching pathway it can choose to go in the one it needs or if the robot, due to unforeseen circumstances gets knocked out of its correct orientation it can get back in the correct one. This does however require that there is some sort of imaging equipment available in order to determine were the robot is an how it should move. Another point of importance is that the movement has to be further investigated in order to know what changes in magnetic field would cause the desired motion. So that the movement of the robot can happen more smoothly and without using trial and error to get the correct motion.

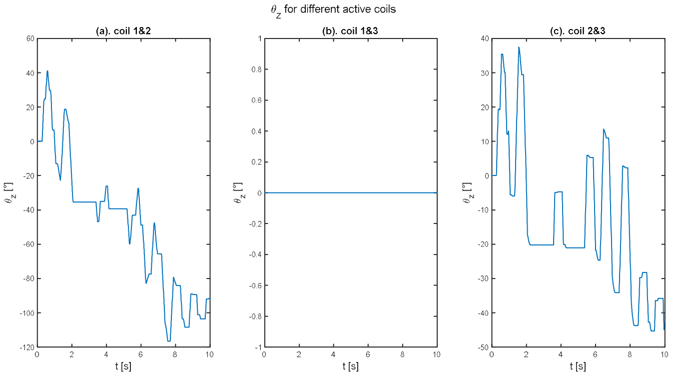


Figure 19: Rotation around the z axis when the magnetic field is along the x axis and different coils are deactivated. (a) simulation of θ_z with coils 1&2 active. (b) simulation of θ_z with coils 1&3 active. (c) simulation of θ_z with coils 2&3 active

7 Experiment setup

7.1 Goal of the experiment

The goal of the experiment is to show that it is possible to alternate the activation of the coil using a periodic signal. Furthermore it will be seen if the coils can generate the magnetic moment that is needed to cause the movement. The original goal was to include a time delay for a second coil and build it out of only logical components but due to time constraints this was not possible.

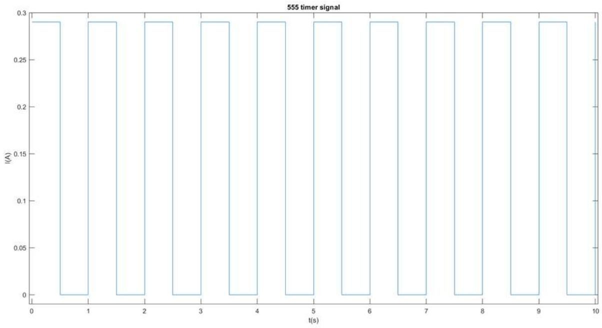
7.1.1 expectations

The expectation for this experiment is that the coil will draw power in an on/off way and create a magnetic moment. Where this magnetic moment is the same as the one that can be calculated using equation 6

7.2 Experiment setup

7.2.1 Signal

A circuit has been build that creates a periodic signal using a 555 timer. The signal that will be created is a pulse signal as seen in Figure 20 This signal emulates the signal that would originate from the Schmitt triggers namely an on/off signal in the form of pulses.



.Figure 20: Example of the current signal created by the 555 timer

7.2.2 circuit

The circuit that has been used to create the aforementioned signal can be seen in Figure 22. In this circuit the 555 timer is used to create an alternating signal that goes through the coil. The major downside of this circuit is that it uses a 555 timer that cannot be downscaled.

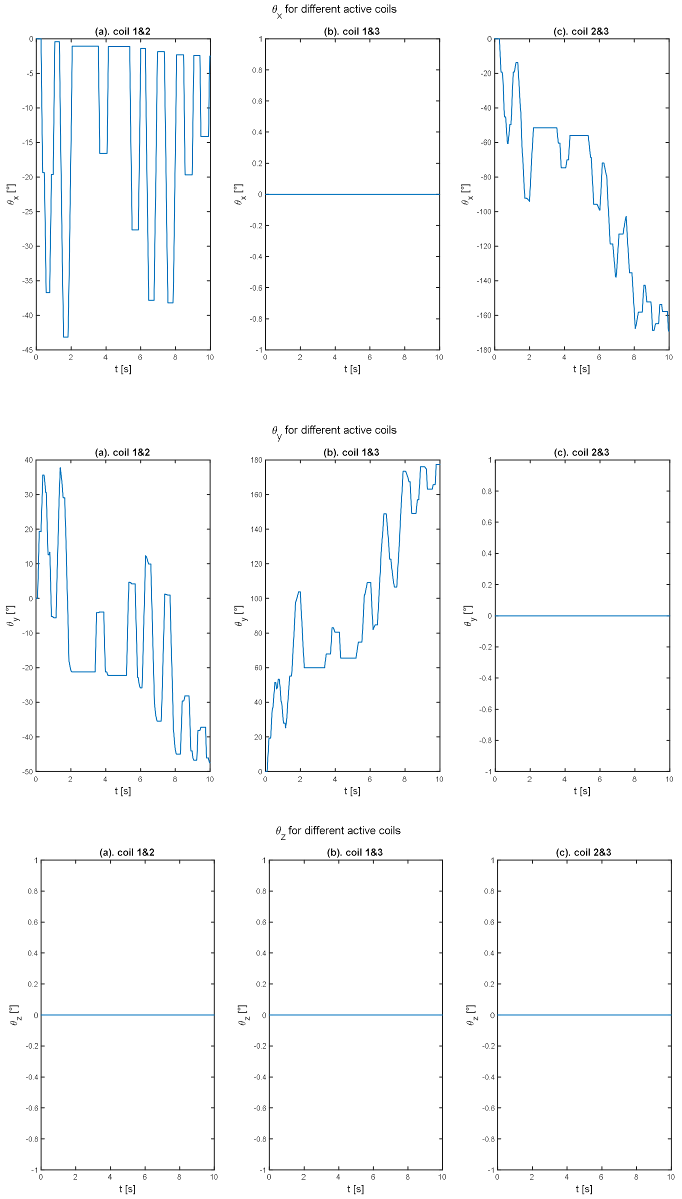


Figure 21: Rotation around the x,y and z axis with different active coils over time with the left graphs having coil 1&2 active middle having coils 1&3 active and the right having coil &3 active . Where the above graph is for θ_x , the middle for $\theta_y$and the bottom for θ_z.

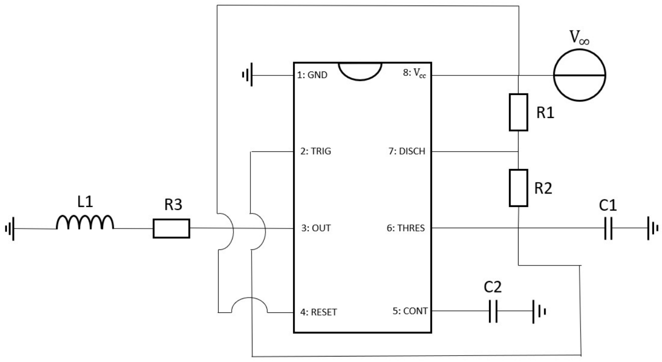


Figure 22: circuit that was used to create the periodic signal with the use of the 555 timer . Where L1 is the coil that will be measured during the experiment.

7.2.3 Measurable variables

The variables that will be measured are the magnetic field created by the coil, the current trough the coil and the alternating of the signal. Since there is no device to measure the current and *magnetic field in real time available this will have to be done by observing the change of current of the mustimeter.*

The measurements are done with the use of a tesla meter and a multimeter. The magnetic field is measured from a distance of 1 mm. A device or a way to convert the analogue signal to a digital signal will have to be found this will have to be done in the coming weeks before the colloquium.

7.2.4 The coil

the coil has been made by hand by rolling a wire around a screw with the diameter of 3mm. The wire has a diameter of 0.2 mm and the coil has 36 turns. The coil that was created can be seen in figure 23.

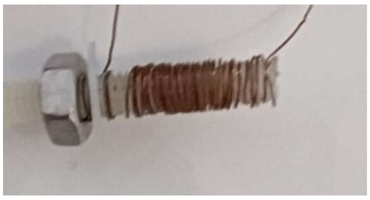


Figure 23: Photo of the coil used in testing. The coil is made using a wire with the diameter of 0.0001 mm wich is wound 36 times around a plastic screw with a diameter of 3mm.

8 Experiment results

8.1 Measured results

the coil created a magnetic field of 0.1 mT with a current of 0.2868 A. It cannot be shown in this document that the magnetic was going in an on/off signal like in figure 20. Since a way to import data to a pc has not been found. But the magnetic field was seen to go on and off in sync with the current going through it.

8.2 calculated results

Using equation(6) the magnetic moment can be calculated. The measured magnetic field was B=0.1 mT at 1 mm distance from that the calculated magnetic moment is 4.9986e-07 Am^2 *and the expected calculated value from the measurement of the coil equals 0.0065* Am^2 *wich would yield a magnetic field of B=1.2978 T*

9 discussion

9.1 simulation

The simulation of the different variables shows that it is possible to rotate the device with the use of micro coils. The model also seems to mostly react as expected to the change of each variable. The only noticeable thing during the simulations is that there seem to be spikes in the signal. These spikes seem to only occur when the movement is made easier by either lowering the variables that influence the resistance of the movement or increasing the variables that promote movement. This is because by change these values the movement will be so rapid that the timesteps will have a very big influence on the results. Since in one timestep the device will have moved so significantly that the coil orientation will not be correct. Because in the real world the coil will align with the magnetic field but since the timestep is to small the coil will overshoot as it where causing the strange behaviour that are the spikes. Therefore the simulation is not applicable for situations where the rotational velocity's are significantly high unless the time step is decreased significantly. Furthermore as discussed in section 6 controlling the movement with only an alternating activation of coils proved too difficult. Since there was no way to make the device rotate around one axis. Because the movement was not completely periodic and therefore could not be accurately predicted. Furthermore the attempts to derive a formula for the rotation around each axis in order to predict the movement failed. Therefore the only options without using complex parts like sensors is changing the magnetic field.

9.2 Experiment

The original experiment did not succeed because of problems during testing that could not be resolved in time. However the current experiment shows that it is possible to create an magnetic field using a periodic signal. However the measured value of the magnetic moment is significantly lower than calculated in theory. The assumption is that this is because of the faults in the manufacturing of the coils since during testing the value of the magnetic moment has been seen to be higher However when it was tried to replicate this result it failed and the measurements where not recorded at the time. This makes it so that the results are inconclusive the predicted result may be possible but have not been measured or been able to be replicated.

9.3 improvements

9.3.1 Simulation

In order to improve the simulation the reliance on the time step needs to be eliminated. This will mean that the simulation has to be made analytically. If this is not possible the timestep will need to be reduced this however will mean that the time of the simulation will significantly increase.

9.3.2 experiment

There are a lot of improvements to the experiments with the most important being adding a time delay to the signal for a second coil. Making the circuit out of only logic component. If these two changes are achieved the focus can shift to looking into how to scale down the components so that it will fit in the device. Furthermore a more consistent and accurate way of making coils can be looked into to mitigate the difference of the theoretical value and measured value. Moreover a way to measure current over time to see what kind of current gets drawn by the coil over time and if it comforts with the expectation.

10 conclusion

From the results it can be concluded that theoretically it is possible to create a millirobot that rotates under influence of a magnetic field with the use of a tri-axial micro coil system. However the control of the movement is very difficult because of the rotation in all directions. Due to the small scale of the robot complex components like sensors cannot be used making it difficult to control the robot with no outside influence.. Therefore other options have to be used like changing the magnetic field.

By the experiment it can be seen that it is possible to create a magnetic moment using an alternating current signal through a magnetic coil. However the circuit that was used cannot be downscaled and needs to be rebuild using only logic components. Moreover the value of the magnetic moment that was measured were significantly lower as the theoretical values. However due to the limitations of the manufacturing process it is not possible to conclude decisively if it is possible to reach the theoretical values. So in the future more testing will have to be done to see if it is possible.

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