EN.530.666 Magnetically Actuated and Magnetic Resonance Imaging Compatible Robots
Lab 4: Magnetic Surgery Lab - PID Control with Dipole Model

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Fall 2025

Due Date: Thursday, February 28, 11:59 PM

February 17, 2025

1 Problem Statement

In this lab assignment, you will explore and implement a closed-loop controller with **dipole model** to control the position and orientation of your magnetic robot as shown in Figure 1. You will accomplish this through i) implement dipole model based steering with a joystick ii) control orientation based on dipole magnetic field calculation iii) control position based on dipole force calculation iv) make the robot follow a trajectory under closed loop control.

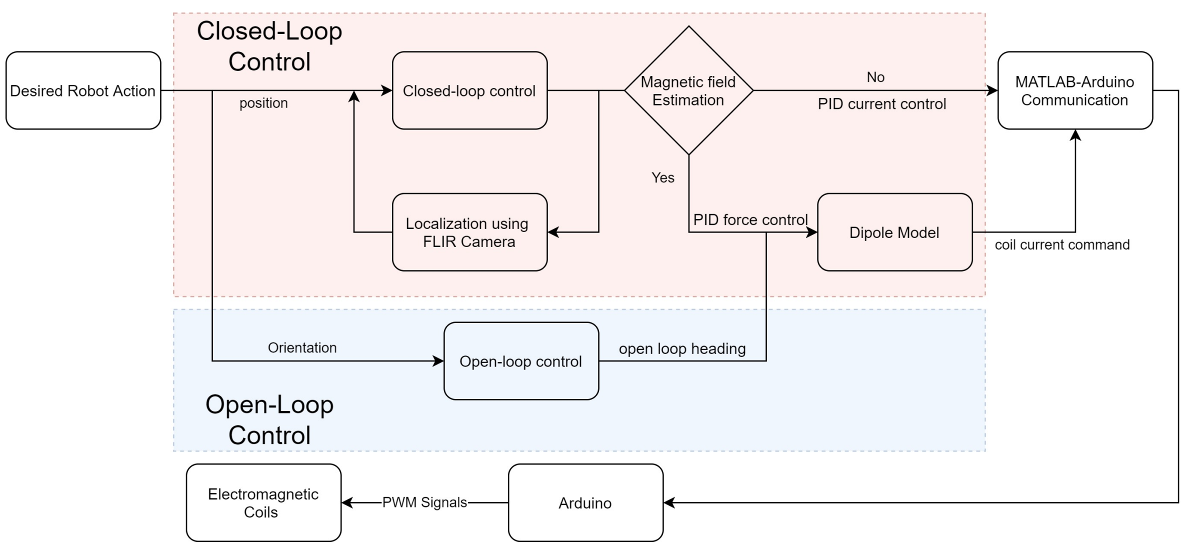

Figure 1: System architecture of the magnetic project.

2 Implement Dipole Model with a Joystick

$$u = \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \end{bmatrix} = \begin{bmatrix} \tilde{B}_{1x} & \tilde{B}_{2x} & \tilde{B}_{3x} & \tilde{B}_{4x} \\ \tilde{B}_{1y} & \tilde{B}_{2y} & \tilde{B}_{3y} & \tilde{B}_{4y} \\ \tilde{F}_{1x} & \tilde{F}_{2x} & \tilde{F}_{3x} & \tilde{F}_{4x} \\ \tilde{F}_{1y} & \tilde{F}_{2y} & \tilde{F}_{3y} & \tilde{F}_{4y} \end{bmatrix}^{-1} * \begin{bmatrix} \alpha \cdot \hat{h}_{des,x} \\ \alpha \cdot \hat{h}_{des,y} \\ F_{des,x} \\ F_{des,y} \end{bmatrix}$$

Figure 2: Use Dipole model to calculate the coil current.

Note: Please only use the robot assigned to your group at all times. Misusing of different magnetic robots would cause inconsistency with the robot performance and endless parameter tuning!

In this section, you will implement the equations (Figure 2) of dipole model derived in class, as shown in Figure 3, to control the robot with a joystick. The left joystick will control the desired magnetic force which controls the location of your robot and the right joystick will control the desired magnetic field of the EM coils. The horizontal output (-1 to 1) of the left joystick will determine $F_{des,x}$ and the vertical output (-1 to 1) of the left joystick will determine $F_{des,y}$. The right joystick will directly map the heading of the robot. Note: you should push the right joystick to the edge to get an accurate desired heading of the robot. If you implement the dipole model correctly, you should see the robot moving in the same direction as the left joystick and the heading of the robot should be same as the heading of the right joystick. The distance between center of each coil to the center of petri dish is 0.08 m. Thus, you can define the position vectors using coil coordinates such as [0, 0.08], [0, -0.08], [0.08, 0], [-0.08, 0]. They should match your definition of the coordinate system and coil orientations.

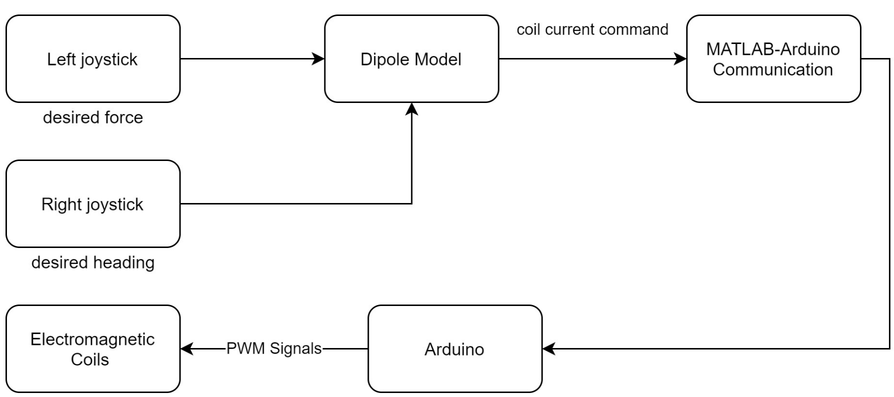

Figure 3: Implement Dipole model with a joystick.

3 Control Orientation Based on Dipole Magnetic Field Calculation

$$u = \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \end{bmatrix} = \begin{bmatrix} \tilde{B}_{1x} & \tilde{B}_{2x} & \tilde{B}_{3x} & \tilde{B}_{4x} \\ \tilde{B}_{1y} & \tilde{B}_{2y} & \tilde{B}_{3y} & \tilde{B}_{4y} \\ \tilde{F}_{1x} & \tilde{F}_{2x} & \tilde{F}_{3x} & \tilde{F}_{4x} \\ \tilde{F}_{1y} & \tilde{F}_{2y} & \tilde{F}_{3y} & \tilde{F}_{4y} \end{bmatrix}^{-1} * \begin{bmatrix} \alpha \cdot \hat{h}_{des,x} \\ \alpha \cdot \hat{h}_{des,y} \\ 0 \\ 0 \end{bmatrix}$$

Figure 4: Control effort using direction of desired magnetic field (i.e. robot heading) based on Dipole model.

In this section, you will implement open-loop orientation control with zero force. You will move you dipole mode from dipolejoystick.m to FeedbackControl.m and replace the joystick command with preset desired headings and zero forces. You will estimate the magnetic field direction with dipole calculation and use it with an orientation open-loop controller to calculate the control effort. $h_{des,x}$ is your desired robot heading in x direction and $h_{des,y}$ is your desired robot heading in y direction. Tune the scalar α to achieve good orientation control, while not needing large currents (less than 20% of max current), which are needed for position control. Move your robot to the center of the petri dish and experiment with different orientations (-45, 30, 45, 90, 135, 180 degrees) and write down your observations in the report. Analyse the error for these angles and record a video when the target orientation is at 45 degrees and -45 degrees respectively. Move the robot to different locations. Does this orientation controller still work?

4 Control Position Based on Dipole Force Calculation

In this section, you will control your robot to move from a start point to a given target point with a desired fixed orientation. You will add coil current control based on the dipole model force calculation to the previous section, where you have oriented your robot along with the magnetic field. You will perform a point to point control with camera localization feedback, where you calculate your position error. Then, you will use PID controller to convert the error into force and map these forces to input current using the dipole model. The start point is the origin. Move your robot to 10 different target points that cover the petri dish, using different orientations (avoid singular configurations). You can compute the determinant of your C matrix to check for singularities. Write down your observations in your report.

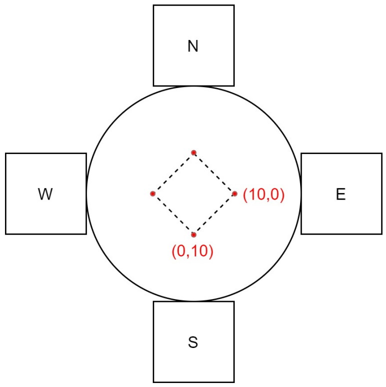

Figure 5: Diamond trajectory.

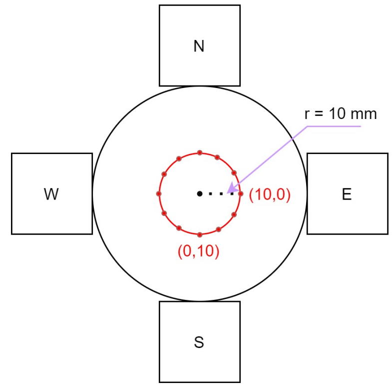

Figure 6: Circle trajectory.

5 Magnetic Robot Trajectory Following Using Dipole Model and PID Controller

In this section, you will use your Dipole model with PID controller to make your robot follow two trajectories as shown in Figure 5 and Figure 6. The waypoints locations and orientations are defined in MagneticSystemBackbone.m. You will choose the trajecoty you are going to run in MagneticSystemBackbone.m. Calculate and report both RMS error and maximum deviation from the planned path for trajectory following.

6 Submission

A zip file per project team (100 points) containing the following items:

1. A single PDF file per project team with a short lab report containing a summary of the lab with the following items:
   - Observation of controlling robot orientations based on dipole magnetic field calculation (different angles) (10 points)
   - Observation of controlling robot position based on both dipole magnetic force and field calculations with PID for 10 different target locations and orientations (20 points)
   - Does dipole model with PID controller perform better than just PID controller (lab 3)? Explain. (10 points)
   - Observation of following trajectories using dipole model and PID controller (20 points)
   - RMS error and maximum deviation of trajectory following (10 points)
2. A video of moving your robot with the joystick both in position and orientation (10 points)

3. Two videos of controlling the orientation of your robot based on dipole magnetic field calculation (45 and -45 degrees) (5 points)

4. One video of point to position control using PID with dipole model (5 points)

5. A video of diamond trajectory following (5 points)

6. A video of circle trajectory following (5 points)

7. A zip file containing all your MATLAB scripts (Required to receive a grade for this assignment)