Integration of Coil Design, Path Planning, and Image Processing for an Autonomous Microrobotic Manipulator

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***Abstract*—In this poster presentation, we designed and manufactured a 4 degree of freedom mobile microrobotic system that can autonomously or manually be actuated to manipulate cargo to a desired pose. We used a 3-axis Helmholtz coil system to actuate the microrobot in all three cardinal directions. A PID controller uses these actuations to have the microrobot track a desired trajectory and reach a correct pose, using an A* path planner to choose the most efficient path. To inform the path tracking controller, standard image processing algorithms are used to differentiate the microrobot and cargo and track their pose in real time.**

***Index Terms*—Microrobotics, Electromagnetics, Path Planning, Path Tracking Control, Computer Vision**

I. Introduction

This abstract is written in support of the University of Toronto's poster presentation for the Mobile Microrobotics Challenge. It presents an overview of the competition tasks, an overview of our methods based on research over the past 30 years, and technical details about the coil design, controls, and computer vision algorithms.

II. Competition Description

The Mobile Microrobotics Challenge (MMC) is an annual competition hosted by the IEEE Robotics and Automation Society as part of the International Conference for Robotics and Automation. This challenge aims to encourage researchers to accelerate the development of microrobots that can autonomously navigate and manipulate objects at the microscale. Currently, several methodologies have been explored in the wireless control of untethered magnetic microrobots [1], and their improvement for the use of this competition will be the main focus of this proposed research.

The MMCs competition tasks are designed to simulate anticipated applications in microassembly, including the manipulation of blood vessels in biomedical projects as well as the assembly of components in nanomanufacturing [2]. The microrobots are designed to be untethered through its control via external magnetic fields, enabling them to be minimally invasive and maximally dexterous in medical applications such as intraocular drug deliveries [3].

III. Overall Approach

Computer vision is the first stage that enables the latter control stages of the microrobot. The algorithm utilizes the functions available within the OpenCV library based on C/C++. It runs on a separate thread in parallel with the path tracking controller thread above. The algorithm consists of an outer loop, which continues to run as long as live camera data is fed into the algorithm. Inside the loop, it first performs preliminary image processing to differentiate the microrobot from the cargo based on sizes and grayscale values. It then determines both of their position and orientation using existing OpenCV functions and custom-written functions. As they move through the field, they are tracked separately by the algorithm in real time, and their pose information is continuously fed into the path planning and control algorithm for their actuation.

Over the past few years, several groups have developed advanced methods for planning trajectories for the intelligent control of multiple robots [4], efficient path planners for quick movements of microrobots with obstacles [5], and state-of-the art actuation techniques to overcome friction [6]. This poster presentation aims to combine these areas of research by developing a path planner and a path tracking controller in a microrobotic closed-loop system that can autonomously navigate towards a cargo and manipulate its pose.

Through a rigorous selection process, it was determined that the optimal settings for the path tracking controller would be to use a 20 cSt silicone oil medium in a smooth cast arena with a polyurethane robot and cargo. The path tracking controller used a combination of gradient pulling, and stick slip motion was implemented to allow the robot to follow a desired position in the arena. The gradient pulling method allows the robots position to be finely controlled with a PID controller, hence leading to relatively smooth and accurate motions. However, the robot can often become stuck to the floor of the arena due to high static friction. To mitigate this, a stick slip motion is implemented by using the vertical magnetic field the robot to have minimal contact with the floor. Path trackings input trajectory is also optimized by using the A* path planning algorithm to ensure that the robots controller tracks the best set of waypoints to follow.

After conducting an extensive literature review, it was discerned that various projects have used tri-axial Helmholtz coils, and each of the respective research groups have redesigned the coils for their own implementations. Therefore, a recent research paper was published in 2015 by J.J. Abbot in Review of Scientific Instruments, which discussed methods to standardize the design of tri-axial Helmholtz coils to be used as an electromagnetic actuation technique for the control of microrobots [3].

The hardware used to actuate the microrobotic system consists of two main components: the coil system and servo drivers. The coil system was designed using the Biot-Savart law to approximate the strength of a magnetic field due to current flowing through a wire. By understanding the strength of the magnetic field, it was possible to determine the smallest possible coil which provides an adequately uniform field. Once the inner coil was designed, the middle and outer coils were designed based on the geometry of the inner coils to create a 3-axis helmholtz system. Servo controllers are used as a means of communication between the computer and the coil system. Once the path-planning code determines the direction the microrobot must move in, a signal is sent to the servo controllers. These then use this signal to provide a current to the coils which creates the desired magnetic field. The servo controllers selected interface directly to the computer via USB for simplicity.

IV. Implementation Details

In the following section, technical details are described that make up the proposed autonomous microrobotic manipulator.

A. Image Processing

Basic functions such as dilation and erosion are used for preliminary image processing to prepare for finding contours. Then, depending on the actual shape of the part, a shape detection function is used to determine the location of the part. Since these functions only return angle values from 0 to 90 degrees, custom functions are written to output the full orientation of the part from 0 to 360 degrees. In addition, an occupation matrix with the size of the frame is created to tell the path planner which areas are occupied (see Fig. 1).

B. Path Tracking Controller and Planning Design

A PID controller is used to output the currents in the amplifier system's electromagnetic coils in order to generate a controllable gradient field. One problem that arose from only using the gradient force was that the robot would be subjected to large static friction, causing unintended accelerations. Therefore, apart from the gradient force, stick-slip motion is also utilized as the main actuation technique to enable the robot to move more easily across its medium.

At each point in time, the microrobot is given a single waypoint to follow, and the coils are controlled to have the robot move towards one point at a time until it is within an empirically found threshold. These waypoints are intelligently found by using the A* path planner. Since the path the robot needs to follow is along a simple two-dimensional configuration space, use the Manhattan Distance is used as an admissible heuristic to ensure that the generated path is always optimal. Only the robot's position is considered in path planning, assuming the robot can be oriented appropriately at each endpoint of its path by using the uniform field to rotate the robot to the required angular position.

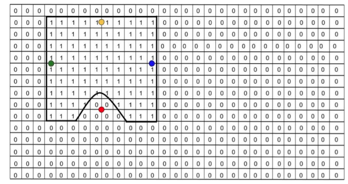
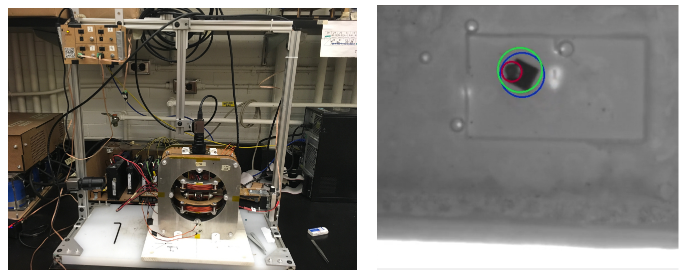


Fig. 1. Occupation Matrix



(a) Coil System (b) Microrobotic Arena

Fig. 2. (a) 3-axis Helmholtz Coil System. (b) Microrobotic system performing the Autonomous Manipulation Challenge.

C. Coil Design

The final coil system used to actuate the microrobot is comprised of three pairs of orthogonal electromagnetic coils to generate a magnetic field in any direction in 3-dimensional space. Each of the six coils is driven independently by a USB servo controller. The independent controls allows for control over both the magnetic field and magnetic field gradient. While the USB servo controllers allow for efficient communication with the path tracking controller.

V. Results

In the latest experiment, the microrobotic system was accurately controlled to complete the MMC's Autonomous Manipulation task within 57 s (see Fig. 2).

References

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