Independent Control of Three Magnetic Microgrippers in Three Dimensions

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I. MOTIVATION

A microrobot is a small-scale robot with characteristic dimensions less than 1 mm. Due to their small size and high mobility, microrobots show great potential for biomedical applications such as disease diagnosis, health monitoring, targeted drug delivery and minimally invasive surgery [1]. While various actuation methods exist for microrobots, magnetic actuation has been identified as a suitable technique for realizing three-dimensional control in confined environments. Since an external magnetic actuation system can safely and remotely generate torques and forces on the microrobot, it is ideal for *in situ* operations [1]. In addition to the utilization of a single robot for these tasks, the capability to deploy multiple microrobots will enable more precise application scenarios as well as significantly improve operation efficiency. While implementing control strategies for a single magnetic microrobot can be relatively straightforward, independently controlling multiple magnetic microrobots is shown to be quite challenging since the robots are subjected to global magnetic fields. In order to realize more complex microbotic applications, overcoming the challenge of multi-agent control has becomes a significant focal point of the microrobots research community in recent years [2]. In this work, we explore different control strategies to enable robust and independent control of three microgrippers in three dimensions.

II. OBJECTIVES

The main objective of the project will be to accurately and independently control three microgrippers in the glycerol fluid. The each gripper will simultaneously draw a number 8 figure in x, y, and z respectively in simulation with added real world noise. The error for the paths of three grippers should be less than 10%.

This goal will be achieved in the following Four steps:

- Create a workable basic 3D simulation environment which can simulate basic physics interactions between the microgrippers, glycerol fluid, and magnetic field.
- Independently control three microgrippers to draw number 8 in their respective planes in the simulation environment with no noise. The location error for each gripper should be less than 10 % .
- Improve the basic 3D simulation environment by adding modelled real-world noises.
- Independently control three mircrogrippers to draw number 8 in their respective planes in the noisy simulation environment, which resembles the real-world environment. The location error for each gripper should be less than 10 % .

III. METHODS

Due to the constraints of the COVID-19 pandemic, we will develop and demonstrate independent control of three microgrippers in a simulated environment. The simulations will be set up using the Gazebo platform with Matlab's Robotic Systems Toolbox and Simulink. The first simulation environment model the basic physics interactions between the microgrippers, magnetic field, glycerol fluid environment, and solid boundary with no environmental noises and parameter errors. The second simulation environment will model real-world noises to accurately represent operation in real-world environments. Starting with a simple PID controller with position and velocity as the feedback control inputs, different control strategies, including Three Dimensional Independent Control of Multiple Magnetic Microrobots via Inter-Agent Forces [3], Control of Multiple Heterogeneous Magnetic Microrobots in Two Dimensions on Nonspecialized Surfaces [4] and etc, will be implemented in the no-noise environment to test their respective theoretical best performance, while the robustness of the controllers will be tested in the close-to-real-world simulation environment. The best performed controller can be chosen based on the simulation result.

IV. TASKS

- Task 1: Learn How to Use Robot Simulation Platforms
  - Task 1.1: Set up Gazebo simulation to Matlab Robotic Systems Toolbox and Simulink. (RC)
  - Task 1.2: Complete simulation tutorials. (JC)
  - Task 1.3: Explore other simulation platforms. (DL)
- Task 2: Model Microgripper and Simulate a Basic Microrobot in 2D Space

This work was completed as a part of the course MIE505 Micro/Nano Robotics at the University of Toronto.

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- Task 2.1: Simplify and model microgripper as a rectangular magnetoelasmer from Lab 1. (DL)
  - Task 2.2: Model magnetic forces and torques of magnetic coils and permanent magnets. (JC)
  - Task 2.3: Simulate simple motion of the microrobot in 2D space. (RC)
- Task 3: Model and Simulate Three Basic Magnetic Microrobots in 3D Space
  - Task 3.1: Model the superposition of multiple magnetic field sources. (DL)
  - Task 3.2: Simulate simple motion of the three microrobots in 3D space. (JC, RC)
- Task 4: Test Independent Control of Three Basic Magnetic Microrobot with no Noise
  - Task 4.1: Implement PID controller for one microrobot in one plane. (JC)
  - Task 4.2: Implement PID controller for three microrobots in perpendicular planes. (RC)
  - Task 4.3: Implement path following for three microrobots. (DL)
- Task 5: Test Independent Control of Three Basic Magnetic Microrobot with Added Noise
  - Task 5.1: Model real-world environment noise. (DL)
  - Task 5.2: Implement designed controller and add simulated noise. (JC, RC)
  - Task 5.3: Design and test control methods to combat noise. Characterize stability and response. (JC)
- Task 6: Fabricate microgripper and test control method in the MIE Microrobotics Laboratory

V. WORK PLAN AND TIME SCHEDULE

- Week 0 (Oct. 13): Finalize project idea, submit proposal
- Week 1 (Oct. 20): Work on and complete Task 1
- Week 2 (Oct. 27): Work on and complete Task 2
- Week 3 (Oct. 30): Work on and complete Task 3
- Week 4 (Nov. 10): Work on and complete Task 4
- Week 5 (Nov. 17): Work on Task 5
- Week 6 (Nov. 24): Complete Task 5, submit report draft
- Week 7 (Dec. 1): Buffer Week for behind-schedule tasks
- Week 8 (Dec. 8): Final report, final presentation

VI. LITERATURE REVIEW

A literature review on relevant topics is conducted based on the following three aspects: control of a single magnetic microgripper, independent control of multiple magnetic microrobots, and accurate representation of real-world environment in microrobotic simulation.

A. Control of a Single Magnetic Microgripper

Previous work have investigated the control of magnetic microgrippers for applications such as drug delivery, microfabrication, and microscale manipulation [5]. Typically, the microgrippers are actuated using external magnetic coils and magnetic field sources that can be superimposed. Feedback control can be enabled through high-resolution cameras to track gripper position and orientation or through Hall-effect sensors to measure current of the coils [5], [6]. Current challenges in microgripper control include precise actuation and orientation control [3], control at the air-water interface [6], and effects of buoyancy and static friction [7].

Diller et. al present a monograph the overviews the physics, mechanics, and design of microrobotics. [5] Included are detailed discussions relevant to the control of magnetic microgrippers. Microgrippers are typically actuated by magnetic fields, which are perfectly suited for microscale and remote environments. Magnetic field sources can independently apply forces and torques to microgrippers. Furthermore, multiple magnetic fields can be superimposed as long as the environment does not contrain soft magnetic materials. These magnetic fields are typically created with external permanent magments or magnetic coils powered by linear electronic amplifiers. In the case of magnetic coils, the applied voltage serves as an additional control input for precise feedback control; an external PC with a high data acquisition rate is typically required to control the currents driving the coils. In the case of external permanent magnets, the microgripper rotation axes can be mapped to the rotation axes of an external permanent magnet. Thus, the position of the magent and the microgripper's motion can be controlled independently.

Localization and control for microgrippers can be further enabled through various tracking methods. The most common is optical tracking, which utilizes high-resolution cameras and machine vision algorihms. [5] However, this method requires line-of-sight and is not suitable for more challenging environments such as inside the human body. Alternative mathods include electromagnetic tracking (which determines a sensor position based on field readings relative to a field emitter), MRI tracking (which uses a MRI machine for time-multiplexed localization), X-ray tracking (which uses attenuated signals to unique densities), and ultrasound tracking (which detects echos of trasmitted sound waves).

Diller et al. present a method to control multiple microgrippers using a magnetic coil system with six independetn coils that enables 6-LOF position control [3]. In this subsection, we focus on the control for one microgripper; in the latter subsection, we focus on how the proposed method enables simultaneous control of multiple microgrippers.

The microgrippers are actuated in 3D space by center-of-mass magnetic pulling in 3D. A microgripper's relative position to other agents is controlled by changing the orientation of a uniformly applied field. A microgripper's global position in the environment is controlled by a magnetic field gradient superimposed over the uniform field.

In their work, Diller et al. proposed and test two different control schemes. Alternative 1 is a p-controller that achieves stability at set points. Alternative 2 has lower tracking errors; it uses an optimization-based controller with a fitness function to creative a weighted sum of corrective radial, azimuth, and polar forces. Since the proposed control schemes only rely on the orientation of the magnetic field, they can be combined with the magnetic control methods.

Diller et al. implemented their method in both simulated and experimental tests. They methods succesfully enables two microgrippers to independntly position and move along preset trajectories. The microgrippers were able to precisely follow reference trajectories in three dimensions and achieve the desired orientation.

The main limitation of Diller et al.'s method is that the orientations of an individual microgripper cannot be independently controlled. If there are multiple microgrippers in the system, their orientations will all be linked and affected simultaneously.

As in Diller et al., Ongaro et al. control a magnetic microgripper using six independent electromagnetic coils [6]. This work proposes a control scheme that uses a combination of position, velocity, and acceleration errors as feedback for magnetic forces. A high-resolution camera measures the microgrippers current position. A machine vision tracker and iterative learning observer are used to track the gripper's position and estimate its velocity and acceleration.

These state estimates, in tandem with the tracked position, are used in the closed-loop controller. Ongaro et al. characterized three design alternatives and showed stable motion control with microgrippers ranging from 100 µm to 980 µm. The authors further identified that weak fields–which have been used to actuate magnetic beads–are not sufficient to precisely actuate microgrippers; rather, stronger magnetic fields were required for microgrippers to release their grasp.

Feng et al. [7] investigated balancing magnetic and buoyancy forces for controlling microgrippers. As in the other works, magnetic coils are used to actuate the microgripper in the x-y plane. However, actuation in the z-direction occurs by balancing magnetic and buoyancy forces. In the experimental setup, maximum buoyancy forces elevated the microgripper to the top of the fluid environment. Conversely, maximum applied magnetic forces lowered the microgripper to the bottom of the fluid environment. The overall control scheme enables robust three-dimensional motion and ability to grip, transport, and release a 200 µm particle in a microfluidic environment.

Due to the challenges of balancing magnetism with buoyancy, the microgripper in Feng et al. had limited motion stability in the z-axis. The work of Feng et al. identified a "dead band" due to static friction when using a glass substrate as the experiment platform. In this regime, the microgripper does not follow the drive magnet due to the static friction.

The works of this subsection provide an overview for the control of a single microgripper. Multiple robust and stable actuation and methods have been proposed. The work of Diller et al. is notable for being the first to demonstrate 3D manipulation of two microgrippers [3]. The multi-agent control of this work is discussed in greater detail in the next subsection. Multiple open challenges remain for microgripper control. Current control feedback is primarily through machine vision; more work is required in alternative feedback methods such as ultrasound. Microgrippers have broad applications–especially in medicine. Current work have only hypothesized on these concepts and have yet to demonstrate working designs in real-world environments. However, research into applying microgrippers to real-world problems is increasing and garnering excitement [5].

B. Independent Control of Multiple Magnetic Microrobots

While there are a variety of well-established control strategies for single magnetic microgrippers, independent control of multiple magnetic microrobots remains a crucial challenge that needs to resolved in order to realize more complex microrobotic applications in medicine, biology, and manufacturing. A team of independently controlled microrobots will allow an extended range of capabilities–such as performing a large number of parallel surgical operations–in an effective and efficient manner. As a result, the development of independent control strategies has been a significant focal point of the microrobots research community in recent years [2].

Researchers have tackled the multi-agent independent control problem with various approaches. Pawashe et al. [8] have demonstrated multi-robot control of untethered magnetic microrobots utilizing electrostatic coupling to a substrate. With the influence of a global magnetic field, the position of two identical microrobots were shown to be controlled independently in two dimensions. This was achieved through the introduction of a surface designed with electrostatic pads that can selectively anchor the microrobots with the global magnetic field. However, the motion profiles of the microrobots are still relatively restricted, where the range of achievable motions are determined by the placement and arrangement of electrostatic anchoring pads.

DeVon et al. [9] have designed a controller that is capable of moving multiple microrobots in the same direction with different speeds. This control strategy was developed using the *Magmite* microrobots previously designed by Frutiger et al [10]. The controller takes advantage of the non-uniformity of the microrobots, where each *Magmite* produces a different motion profile based on different resonance frequencies. While the motion direction of the microrobots can be altered through rotating magnetic fields, they remain restricted to a motion profile in the same direction given a single global input magnetic field.

Diller et al. [4] have developed a method for independent position control of heterogeneous magnetic microbots in two dimensions. In this approach, the control strategy was implemented on the *Mag-μBots*, which were fabricated to exhibit different responses to the same actuation magnetic field. Utilizing this heterogeneous behaviour, it was shown that the three *Mag-μBots* can be simultaneously controlled to reach independent goal positions in a coupled manner.

Nevertheless, methods that heavily rely on specialized surfaces or heterogeneity of the fabricated microrobots are observed to severely limit the achievable motion profiles of independently controlled microrobots. These restrictions result in poor scalability of the produced control strategy as well as the ability to perform complex tasks. Therefore, in order to establish truly independent control of a large quantity of microrobots, new approaches that avoid the utilization of these concepts have emerged in recent years.

Wong et al. [11] have demonstrated the control of two identical magnetic microrobots in two dimensions without the usage of any specialized substrates. This was accomplished using an actuation system of four stationary electromagnets placed with the coils perpendicular to the plane. Different actuation forces on identical microrobots at close proximity can be realized by taking advantage of the spatial variation of the generated magnetic field gradients close to the coils. With this setup, the microrobots can be driven simultaneously at various locations with the same velocity, as well as along differing trajectories. However, this approach does not allow the microrobots to navigate to any arbitrary location within the workspace due to the dependence on spatial representation of the magnetic field.

Yousefi et al. [12] also developed a magnetic actuation system that is capable of controlling two identical magnetic microrobots in a plane. The system consists of a pair of Helmholtz coils that can generate a uniform magnetic field that controls the direction of the microrobots. In addition, the system includes four rotating magnets responsible for creating the required magnetic field gradient. With this actuation system, the control inputs can be obtained analytically, which can significantly improve the computation time required. Nevertheless, this approach suffers the same constraint where independent control is not achievable for any arbitrary location within the workspace.

Diller et al. [3] introduced a method to independently control a pair of magnetic microrobots in three dimensions utilizing inter-agent forces. A global magnetic field is applied that controls the global center-of-mass position of the two robots, the grasp/release action of the micrograppers, as well as the regulation of the relative position of the robots through local magnetic interaction modulation. The independent control of two functional microrobots in three dimensions with motion profiles along any arbitrary trajectory was demonstrated in simulation and through experiments.

In Diller et al.'s setup of two magnetic microgrippers, the underlying control principle is also generalized into the form of an optimization-based controller that could enable the independent control of microrobots in greater quantities. While the orientation of the microrobots will always be coupled in this approach, it is proposed that this could potentially be resolved through the development of a more general case, where an arbitrary non-uniform field can be patterned across the workspace.

Overall, it is a quite challenge task to achieve independent control of a large number of microrobots. A wide range of strategies have been deployed by researchers to realize this ultimate goal. In addition, a key aspect of developing robust and scalable control algorithms for multi-agent microrobotic systems is the accurate modelling of microscale forces, e.g. surface tension, surface friction, viscous forces. A more precise and reliable simulation of these microrobotic interactions will enable more robust control algorithms.

C. Accurate Representation of Real-World Environment in Microrobotic Simulation

Due to limited access to physical prototypes of the microgripper, we will use simulations to evaluate different control strategies. Therefore, creating a simulation environment that accurately models the real-world environment will be necessary to obtain a meaningful comparison between the performance of different controllers. This means that in addition to the normal physical interactions among microgrippers, magnetic field, and the fluid environment, environmental noises, observation errors, environment errors, and wall effect must also be considered.

Boudaoud et al. [13] discussed how to characterize the noise in millimeter sized micromanipulation systems. Specifically, it provides a method that models a microscale cantilever's dimension, stiffness and resonance frequency to closely resemble milimeter-sized micromanipulation systems such as microgrippers. Boudaoud et al. also modeled noise using the numerical solution of the *Euler-Bernoulli* equations using a finite difference method.

As one of the main goal for the project is to evaluate the performance of different control strategies in a close-to-real-world environment, Boudaoud et al.'s work provides information about the source of noise that can potentially be added in our simulation environment.

Boudaoud et al. studied two main source of noise. The first is ground motion, which consists of fast and slow motions. The slow motions usually relates to the activities of earth. It is concentrated below few Hz which does not have a significant impact on the micromanipulation system. The fast motions are the dominant factors for the ground motion noise, which caused by external factors that cause ground vibrations. The second souce of noise is acoustic noise. It is caused by the sound wave generated from different sources in the environment. Both of these noise can be modeled as a state space model and numerically solved given experimental measured initial condition.

For our project, the initial condition can be any random values. Although these noises might not cause any error for people in everyday life, the energy stored in the wave is significant enough to have a noticeable impact in a microgripper system, where each microgripper only has length at the magnitude of 1mm.

In addition to environmental noise, parameter errors will also affect the performance of the controllers. In the work by Arcese et al. [14], it discussed about how to model the parameters and positional errors which is similar to the real-world environment to test the robustness of their proposed controller. The accuracy of the robot's position is $100\,\mu\mathrm{m}$, which is modeled by a white Gaussian noise on the position output. This is the general resolution of the current medical imaging device.

Using this noise to simulate the real-world position input error will make the simulation more realistic. Furthermore, the input parameters for the micromanipulation system, such as fluid density, magnetic material density, Young's modulus, magnetization, and etc, will have error as well. The error can be, sometime, as large as 20% . Therefore, adding percentage error as Gaussian white noise will be a good simulation for the real-world environment.

Besides environmental noises and input and parameters errors. The wall effect is a common phenomenon that microgrippers will encounter in a real world scenario. Wall effect means when a microrobot is travelling near a solid boundary, the drag force exerted by the microrobot will increase. Including wall effect in the simulation will be a good method to test the robustness of the controller in the simulation environment. The wall effect is discussed in detail for a sphere in low Reynolds number environment in [15].

The microgripper can be simulated as the sphere. When the sphere is doing translational motion near a solid boundary, the drag force which the sphere exerts will increase non-linearly as the distance between the sphere and the solid boundary decreases. The effect of the wall effect will be a dominant factor when the microrobot is close to the wall. Therefore, in order to accurately represent the micromanipulation system in the simulation, wall effect should be considered.

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