Magnetically-actuated mobile micro-grippers for single-cell capture: A theoretical feasibility study

Shenrui Pan[†], Mohamad Akkawi[‡], Adam Schonewille[+], and Sidhanth Moolayil[*]

***Abstract*— Single cell analysis studies the behavior of single cells, addressing the cell heterogeneity issue of samples. Live-cell imaging is better than conventional single cell analysis techniques in non-perturbative dynamic analysis, but requires an effective single-cell capture and containment device. Despite the developments of microfluidic devices, optical traps, microwells and grippers for single cell capturing, a platform for non-perturbative measurement of a captured cells 3D surface molecular expression was in need. Gracias et al. developed a single cell micro-grippers to address this issue. With a suitable magnetic actuation system, the passive actuation of the micro-grippers can be replaced by controlled magnetic actuation for an increase in cell capture yield. In this research, we aim to test the feasibility of modifying the micro-gripper developed by Gracias et al to be mobile. After the proposed modification, the micro-grippers can serve as an ideal platform for selective single-cell capture.**

***Index Terms*—Single-cell analysis, mobile microrobotics, micro-grippers, soft magnetic materials, magnetic actuation system, live-cell imaging.**

I. INTRODUCTION

A. Single cell analysis

The process of isolating a single cell from a heterogeneous population for analysis is an important active research area for understanding the role of sub-populations in cell cultures. Tumors, as an example, consist of a heterogeneous population of cells with different proliferation rates, phenotypes, genotypes, metastatic potential, and drug responsiveness [1] [2]. Much research is still needed in order to better understand how these heterogeneities affect tumor development, however due to the relatively large size of sampling tools for biological analyses, biopsied samples inherently contain large populations of cells. As a result, the data collected from can only be considered as averages and the characteristics of the cell population of interest remain unclear. Additionally while progress is being made, it is still difficult to draw conclusions about the dynamic behavior of single cells from a large population [3]. Single cell analysis allows the behavior of a single cell to be distinguished from its larger cell population, which facilitates understanding of sub-population roles in a heterogeneous cultures to extend to full tissue systems -an exciting prospect if feasible. These observations are particularly important in the fields of genomics, hematology, proteomics, cancer biology, and stem cell biology [3]. Furthermore, through the study of single cell behaviour, there is potential to accelerate the advancements in the fields of regenerative medicine, cancer treatment, and autoimmune disease treatment [4] [5].

Currently, there are a number of different techniques for single cell analysis including DNA sequencing, protein arrays, mass spectrometry and fluorescence activated cell sorting analysis [6]. The disadvantage of these techniques however is that cell lysis is required to perform them. Cell lysis disturbs and destroys cell structures, and the dynamic analysis of cells in the culture environments impossible. Due to this limitation, researchers turn to another technique, live-cell imaging, for dynamic analysis of single cells over greater periods of time.

Live-cell imaging is the means of studying the cellular dynamics of living cells under a microscope over long periods of time in order to ascertain a better understanding of their biological functions. To perform live-cell imaging, an effective way of capturing and containing individual cells is required. Several techniques and devices have been developed to address this issue including microfluidic devices, optical trapping, microwells, and grippers.

Droplet-based microfluidics for sorting single cells has been developed that allows cells to be sorted and isolated at up to 200 cells per second using fluorescence to distinguish between desired specimen [7]. Once a cell is isolated, the dynamic behaviour can be studied over time. Some research groups believe that studying cell behaviour to compressive or shear forces is an important area with not enough research, a technique that is not possible with this system.

Optical tweezers use optical gradient or scattering forces in order to manipulate single cells within a solution with high specificity and spatial resolution. The major disadvantages of optical trapping techniques are the possibility of cell damage due to high optical energy density and the dependence of trapping efficiency on cell flow speed through the media.

Microwells consist of an array of tiny wells or shallow indentations on a flat plate which are specifically designed to be able to hold only one cell of the size of interest. Microwell arrays can be easily manufactured to any specified sized using photo-lithography technology and polydimethyl-siloxane (PDMS) replica molding. Unfortunately, most microwell systems often rely on expensive and bulky micropipetting setups for placing and observing cell [9]. Furthermore, due to the plasticity of many cell cultures, it is not guaranteed that each microwell will only capture one cell.

Lastly micro-grippers are considered for their ability to capture single cells for analysis. Many different types of micro-grippers exist [11], [12], but this project focuses on

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the micro-grippers designed and fabricated by Gracias et al for single-cell capture. The current micro-grippers developed by this group are able to passively actuate, folding up over time and statistically capturing cells in a cell media with little control about the type of cell captured. In partial collaboration with this group and Shenrui Pan, we explore the possibility of making these microgrippers mobile and extending that to single-cell capturing.

It is important to note the difference between Shenrui Pan's research and this study. Pan's research is about the addressable and non-addressable control of the micro-gripper arms for a fixed micro-gripper array fabricated by Gracias' group. This study explores the feasibility of modifying these fixed micro-grippers and actuating them in a mobile fashion.

These micro-grippers developed by Gracias et al show great potential for single-cell capturing, an essential procedure for single cell analysis and could be improved further by enabling mobile actuation.

II. PROJECT OBJECTIVES

The purpose of this project is to study the feasibility of extending the single-cell micro-gripper designed by Professor Gracias' Research Group to incorporate mobile locomotion. We hypothesize that magnetic forces can be used to translate the micro-gripper in a holonomic motion, and that magnetic torques can be used in the opening of the micro-grippers arms. Furthermore, we hypothesize that the residual stress in the current grippers that causes them to fold up will be maintained and act as a restoring force when the magnetic field is removed and closing to capture cells is desired. If our hypotheses are true, it should be possible to open the micro-gripper, move it to a desired cell location and remove the applied field so that the gripper will close around the free-floating cell. We also assume that once a cell is captured the micro-gripper will sink to the bottom of the solution where it can be retrieved and the cell can be studied. The main uncertainty is how feasible this task is at such a small scale.

In specific, we want to use a permanent magnet to apply the magnetic forces and torques on the micro-gripper. To manipulate the position and orientation of the permanent magnet and be able to control the applied field at the gripper, the magnet will be mounted to an industrial robotic arm with the required high precision and accuracy. We chose a robot arm and permanent magnet setup because we want to use the gradient components of the generated field to pull the mobile robot in a desired way and the motion may require dexterous control of the permanent magnet to achieve. In addition, the current magnetic actuation methods available to us can not supply a large enough gradient, therefor we will rely on this technique to try to validate our experiment. Because an industrial robot is very expensive and out of the project budget, we will utilize ROS and Gazebo plugin to simulate our robot arm and the dynamics between it and the micro-gripper. ANSYS finite element analysis software will be used to determine the expected magnetostatic characteristics of the micro-gripper-permanent magnet interactions as well as resulting deformation using solid mechanics simulations.

A. Metrics of Success

We will consider mobile locomotion of these micro-grippers to be feasible if the following are shown:

- The size of the cubic actuating magnet needed should not exceed a side length of 3" which is what we consider to be the safety limit for magnet size.
- The magnetic field required to saturate the grippers can be achieved with the chosen permanent magnet when the magnet is at least 100 mm away to ensure that there is room for the gradient to be changed while keeping the micro-gripper magnetized.
- The micro-gripper can be opened "fully" to 90° with the applied magnetic saturation field.
- The distance from the sample to the actuating magnet should be greater than 20 mm to ensure that there is room for the sample and environment to be supported and for there to be no collisions between robot arm and environment.
- Position locomotion via gradient pulling in Gazebo simulation is successful.
- A desired linear path can be followed in Gazebo and qualitatively validated for minimal error.

In consideration of the time length of the project we will not consider the following aspects in this project when defining feasibility:

- Showing 3D gradient pulling in Gazebo as this would require more complicated algorithms to be implemented for control.
- Showing that selective single-cell capturing in open cell media is possible through experiment.
- Distinguishing and isolating the micro-gripper and captured cell following the capturing procedure.

III. METHODS

A. micro-gripper Fabrication

The single-cell micro-grippers studied in this project have a manufacturing protocol developed by Dr. Gracias' group at John Hopkins University using metal evaporation and e-beam lithography. The micro-grippers can be manufactured on either silicon or glass substrates with the same end result. Initially, a layer of Germanium is patterned onto the substrate to act as a sacrificial layer that is biologically-compatible with cells. Next, a bilayer consisting firstly of SiO 10 nm thick and then of SiO_2 15 nm thick is patterned on top of the germanium sacrificial layer in the shape of the unfolded gripper. The dimensions of this patterned geometry shown in Figure 1 were chosen carefully such that once the gripper is close there is only enough room for a single cell, ensuring single-cell capture. After patterning the bilayer, iron is deposited onto each of the 4 arms in a triangular pattern as well as on the base in a square shape. This layer of iron is 200 nm thick but could be increased to 400 nm thick before irregularities in manufacturing begin to occur. Due to their small size and patterned fabrication techniques, an array of hundreds of micro-grippers can be fabricated on a single wafer with little additional cost. A cross section of the

micro-gripper components during fabrication can be seen in Figure 2.

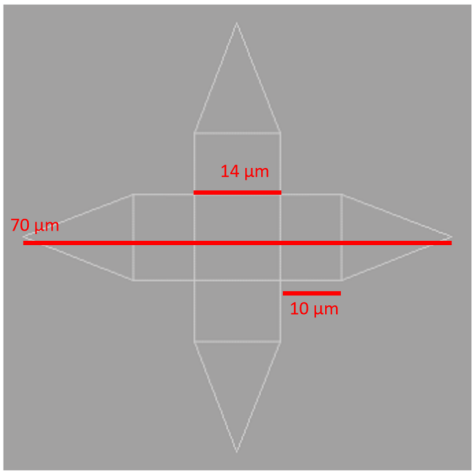

Fig. 1. The geometry of the single-cell micro-grippers. The tip to tip size of the micro-grippers is 70 μm, which was determined to be the optimal size for capturing a single MDA-MB-231 breast cancer cell. These claw-like micro-grippers have 4 arms that fold up to capture a cell that has situated itself on the grippers base. Each arm can fold up to past 110° from the horizontal to completely cover and contain the cell inside.

During the fabrication process, residual stresses build up in the SiO and SiO_2 bilayer wherein the layers tend to fold inwards in a self-assembling manner. The sacrificial and bio-compatible layer of Germanium holds the bilayer attached to the substrate, but can be dissolved away with the addition of water allowing the arms of the micro-gripper to fold up. With the sacrificial layer dissolved the single-cell micro-gripper is released from the substrate completely and becomes free-floating. Furthermore, the sections of the arm not coated in iron act as flexure joints, whereas the iron provides the other sections with the rigidity to maintain its initial out-stretched configuration. Each arm folds up to an angle greater than 110 ° from the horizontal configuration such that the micro-grippers will be normally closed when no external magnetic field is applied.

B. Magnetic Actuation

The iron coating not only provides structural support, but also acts as the magnetic material to be used in facilitating magnetic actuation of the gripper arms. Due to the relatively small size of the iron layer, each arm cannot hold a magnetic moment and instead acts as soft magnetic bodies. As described by Abbott et al, a soft magnetic body will magnetize with the application of an external magnetic field depending on the magnetic material geometry and the direction of the magnetic field [14]. This magnetization direction and magnitude is well described for an ellipsoidal shaped soft magnet, but this is not the case for the triangular shaped iron bodies on the micro-grippers of this study. Due to the triangular-shaped iron arms of the grippers being longer than they are wide we approximate them as ellipsoids when

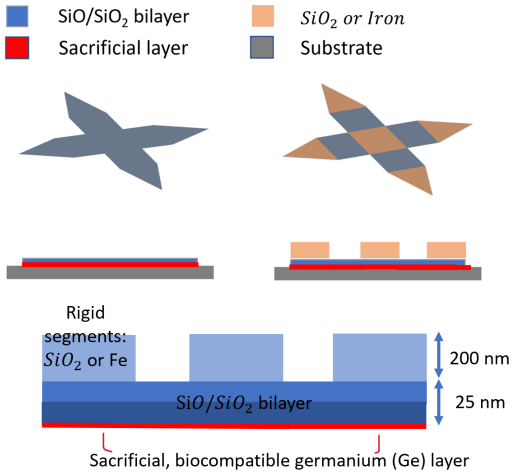

Fig. 2. A cross section of the single-cell micro-grippers. The bottom layer of the single-cell micro-grippers are made of SiO and SiO_2 of the thickness of 25 nm. The center of the body and the 4 arms of the micro-gripper are coated with iron of 200 nm thickness.

hypothesizing the resulting magnetization direction. This allows for the torques and forces generated on the gripper arms to be predicted and verified in FEA simulation.

Using the ellipsoidal assumption, if a uniform magnetic field is applied perpendicular to the base of the micro-gripper we expect that the folded arms will be magnetized nearly along their length and open to align with the external magnetic field due to the magnetic torque applied on the micro-gripper arms. Furthermore, these iron bodies will be saturated with a large enough magnetic field and have a constant magnetic moment. In this respect, even if the applied field changes over the length of the arms, as it does in a gradient field, the magnetic moment will not be affected as long as the smallest field value is still greater than the saturation field. With a magnetic moment and a spatially varying magnetic field a force will be applied to the micro-gripper according to:

$$\mathbf{F} = \nabla(\mathbf{m}_{sat} \cdot \mathbf{B})$$

Where $\mathbf{m}_{sat}$ is the net magnetic moment of the micro-gripper when saturated and $\mathbf{B}$ is the applied external magnetic field consisting of gradient components as well as having a magnitude of at least B_{sat} (the saturation field of the micro-grippers).

The paradoxical conundrum of these micro-grippers is that they must be magnetized in order to apply a force to them. This means that it would be theoretically impossible to move the grippers while keeping them closed because in order to move them with magnetic force using gradient terms the gripper would need to be magnetized meaning that a non-zero magnetic saturation field would need to be applied. However the applied saturation field also applies a torque to open the gripper arms while magnetizing them.

For this reason, we propose a method of single-cell capture that abides to these restrictions. The proposed method of

actuation is shown in Figure 3. The ex vivo procedure will consist of a petri dish of cell media with the mobile, untethered micro-gripper at the bottom of the dish and initially closed due to residual stresses. When an actuating magnet is brought close to the sample environment, the applied magnet field magnetizes the micro-gripper causing its arms to unfold to 90 °. The applied gradients will be used to pull the micro-gripper to a desired cell of interest. Once the open gripper has surrounded the cell it wants to capture, the actuation magnet is quickly removed and the gripper will demagnetize in the absence of a magnetic field. With the applied fields and thus applied torques removed, the micro-gripper will fold closed again, capturing and containing the cell that it was surrounding. The cell and micro-gripper will then sink to the bottom of the cell media container (density of media dependent).

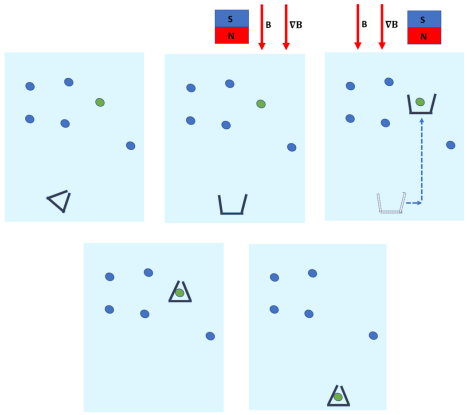

Fig. 3. The proposed technique for single-cell capture with the micro-gripper. Initially the micro-gripper is folded up in a bath of cell media. An applied magnetic field and gradient are used to magnetize, open, and translate the micro-gripper to a desired cell of interest. Here the mangetic field is removed and the micro-gripper closes around the cell, capturing it and falling to the bottom of the solution due to gravitational forces.

C. Actuation Assumptions and Justifications

This proposed method of cell actuation and capturing comes with several assumptions that we will address in this section. We will describe what is possible and what is outside the scope of this project.

Firstly, it is acknowledged that the applied magnetic field must always be in the same direction as the heading of the micro-gripper with sufficient strength to saturate and magnetize the gripper in order to manipulate it's position. This means that the heading of the micro-gripper cannot be changed by simply applying a perpendicular field to torque the microrobot as would be possible with a hard magnet. To get heading control we assume that the change in the direction of the magnetic field is quasi-static such that magnetization of the gripper is hardly affected, and gradient pulling can be used instead. The problem of having precise enough localization to achieve this is assumed possible and considered out of the scope of this project. Next we assume that the field is always perpendicular to the base of the micro-gripper such that it does not magnetize and does not need to be considered. This can be justified in that the direction of the magnetic field is nearly always aligned with the hard axis of the base resulting in little magnetization. Furthermore, it would be possible to fabricate this component of the micro-gripper with a non-magnetic material that is still rigid for support, but could be ignored magnetically.

Finally, we do not consider the fluid effects on micro-gripper and cells in this project.

There are some hypotheses about our proposed method that we want to justify through simulation. It is necessary to know if the gradients across the micro-gripper will be sufficiently high to maintain saturated magnetization. In addition, we want to confirm that when a magnet is placed above the micro-gripper and applies a magnetic field, the arms are torqued open. From this simulated applied torque, it is desirable to know if the arms will fully open to be able to claim that it is feasible to surround and capture a single cell.

D. ANSYS Simulations

The primary purpose of the simulations done in ANSYS is to ensure the deformation in the micro-gripper geometry implemented by a magnetic torque is ideal for the function of the micro-gripper. To reduce computational overhead in the meshing and FEA, the scale of the micro-gripper is increased 1000 times. The permanent magnet will also be sized down in the simulation for the same purposes. Basic scaling laws are derived and used in evaluating the simulation results for actual scale micro-grippers. The initial bending angle is assumed to be 120° from the arms position before the degradation of the sacrificial layer.

The simulations in ANSYS are done in two parts. To begin, an ANSYS Magneto static simulation was used to simulate an applied magnetic torque on a micro-gripper arm from a permanent magnet. An estimated gripper magnetization value can be obtained here to be used for future Gazebo simulations in controlling the micro-gripper. ANSYS Static Structural simulations will then be used to simulate the mechanical deformation of micro-gripper arms under different bending torques to conclude a minimum bending torque required to open gripper arms. The ultimate goal of this is to validate the function of the glass bilayer as a hinge for the gripper arms.

In ANSYS magneto-static simulation, as can be seen in Figure 4, a 20 mm sized cubic magnet is placed 30 mm away from the base of the gripper, which serves as both a magnetizing source to magnetize gripper arms and an actuating source generating torque in bending the gripper arms. The permanent magnet is directly above the micro-gripper, meaning the magnetic field on each arm is the same due to the symmetry in the designed geometry.

When actually developing this gripper, a magnet with the same dimensions of the gripper is not easy to find or afford. Instead, due to the scale independence of the magnetic field, the same magnetic field can be easily generated by

a larger magnet placed a larger distance from the micro-gripper to produce the same local field strength and induce the necessary torque to bending the gripper'arms.

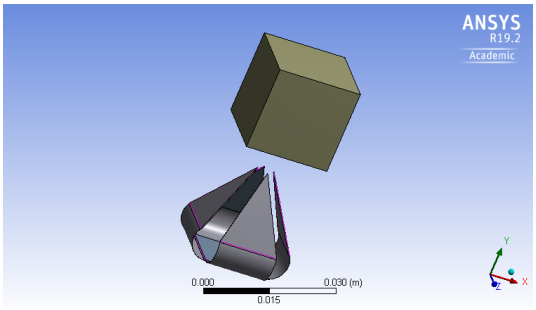

Fig. 4. Geometry setup for ANSYS Simulation

In ANSYS static structural simulation, the SiO/SiO_2 bilayer is represented with a single layer to increase the element size for meshing process. To predict for the bilayer though, both SiO and SiO_2 will be assigned to the layer and analyzed to find a lower and upper bound of the gripper arm deformation.

The Young's modulus for SiO glass is chosen to be 93 GPa and the modulus for SiO_2 glass is chosen to be 73 GPa. The Poisson's ratio for both material is kept at 0.15.

As can be seen in Figure 7, only half of the gripper is studied due to the symmetry of the micro-grippers. This not only decreases the computation time needed for meshing and solving, but also enables us to observe the base deformation due to the applied torque in addition to and from the arms.

E. Gazebo Simulations

The magnetic torque from the B field generated by a permanent on a 6 degree of freedom serial robot can in principle move the actuator magnet into any desired pose to produce the inverse dynamics that the micro-gripper requires.

The four central state sets of interest for a mobile micro-gripper are locomotion from pose A to B while remaining closed or open and the ability to transition between an open to closed state without movement for cell dynamic testing.

The Gazebo simulation can include a robot arm that was physically not available to us. Furthermore, the simulation produces accurate localization of the micro-gripper and thus does not requires a high-quality dynamic camera to localize the initial pose of the gripper which is essential for path planning the heading approach of the actuator magnet. The trajectory planning uses a high order trajectory which plays an important role in the control of the inverse dynamics of the micro-gripper. Nonetheless, localization is part of the scope of this project and is assumed to be possible with a real camera and assuming the noise model is understood, we can confirm the feasibility of localization by adding a simulated camera with noise.

We can also confirm the required B field to both keep the gripper open and move it from one pose to another under the influence of gravity and disturbances such as fluid drag and intrinsic camera noise.

The simulation takes in joint trajectories that are produced by quick analytical solver for the inverse kinematics between the actuator magnet and frame zero. Thus, this approach allows for quick and iterative optimization of redundant degrees of freedom using solvers that are readily available on software's such as MATLAB.

Thus, Gazebo sets up the potential for large areas of analyze for the feasibility and optimally of using the existing fixed micro-gripper as a mobile gripper.

Using the simulation or experimental results, the dipole moment can be calculated for the micro-gripper. Furthermore, given the required torque to produce the required opening angle, we can calculate the minimum distance required to open the gripper up to 90 degrees.

Gazebo allows for simulating multiple magnet interactions under the dipole model. Thus, a second permanent magnet can be used to move the micro-gripper independently from its arm state using only forces due to a uniform magnetic field. In other words, the gripper can capture a cell and remain sufficiently closed while moving the cell to its target pose. It may be possible to redesign the gripper such that it is stiffness is higher where a slight torque from one permanent magnet is not enough to reach an opening threshold.

Under a uniform horizontal magnetic field, it may be possible to close the gripper beyond it's equilibrium of angle of 120 degrees without movement in the global frame. However, further magnetic simulations should be done to confirm this possibility.

In the scope of this project, we were able to successfully test an actuator trajectory and output the forces, torques and B-Field that were applied on the micro-gripper with time.

The actuator moves in a fashion that is similar to the path shown in Figure where the gripper is expected to follow along.

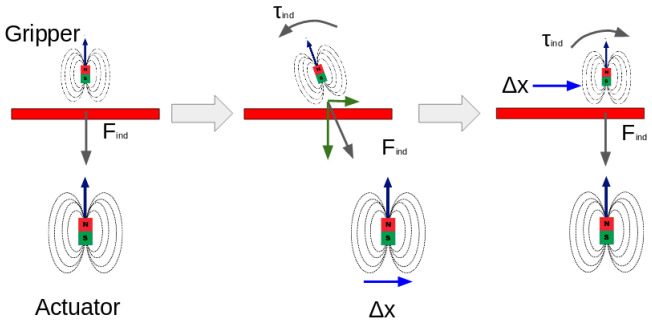

Fig. 5. 1D Forward Dynamics.

IV. RESULTS

A. ANSYS Simulation Results

The magnetic flux density in the location of the micro-gripper arm is simulated, as can be seen in Figure 6. The average of magnetic flux density in the micro-gripper arm is 1.7959 T and the minimal magnetic flux density in micro-gripper arm is above 0.59 T, which is larger than the required magnitude (0.377 T) to saturate the iron layers. This

simulation shows that the micro-gripper is saturated under the magnetic field induced by the permanent magnet. In this case magnet moment of the gripper is maximized, which is ideal for the magnetic driven locomotion of the micro-gripper. The opening torque induced by magnetic field is simulated to be $3.1287 \times 10^{-3} Nm$.

Given the applied torque on the arm of the micro-gripper and the average magnetic flux density across the micro-gripper arm, the net magnetic moment of a micro-gripper arm can be estimated by

$$m = \frac{T}{B} \tag{1}$$

, where m is the net magnetic moment of the micro-gripper arm, T is the overall torque acted on the micro-gripper arm and B is the average magnetic flux density across the arm. The magnetic moment from the simulation is calculated to be $1.7406 \times 10^{-3} Am^2$. Since we know the magnetic moment

$$m = M \times V \tag{2}$$

, where M is the magnetization of the material and V is the volume of the magnetic material. As a result, for the scaling property of the magnetic moment, we expect $m \propto L^3$, giving the simulated magnetic moment value for the real micro-gripper to be $6.9624 \times 10^{-12} Am^2$. However, the experimental magnetic moment value we get from the iron hysteresis curve is $1.3547 \times 10^{-10} Am^2$. We believe the simulation error is due to the small size of the enclosure in ANSYS Magnetostatic simulation. As a result, the experimental magnetic moment value is used in Gazebo simulation.

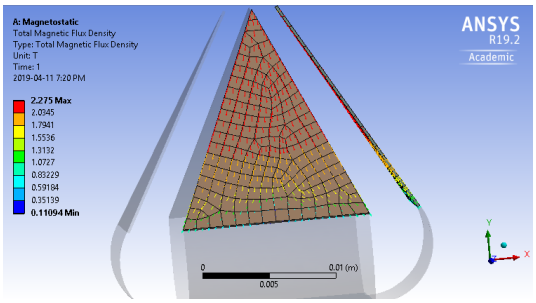

Fig. 6. Simulated total magnetic flux density on a micro-gripper arm.

The deformation of the micro-gripper with SiO_2 base can be seen in Figure 7. The minimum bending torque for bending the gripper arms to a near 90° bending angle is obtained by trial and error, which is $1 \times 10^{-3} Nm$ in simulation.

The deformation for a micro-gripper with SiO base can be seen in Figure 8. The minimum bending torque for bending the gripper arms to a near 90° bending angle is obtained by trial and error, which is $1.5 \times 10^{-3} Nm$ in simulation.

Given the simulated magnetic torque is larger than the required bending torque for opening micro-gripper arm, we prove the feasibility of opening the micro-gripper arm with a permanent magnet.

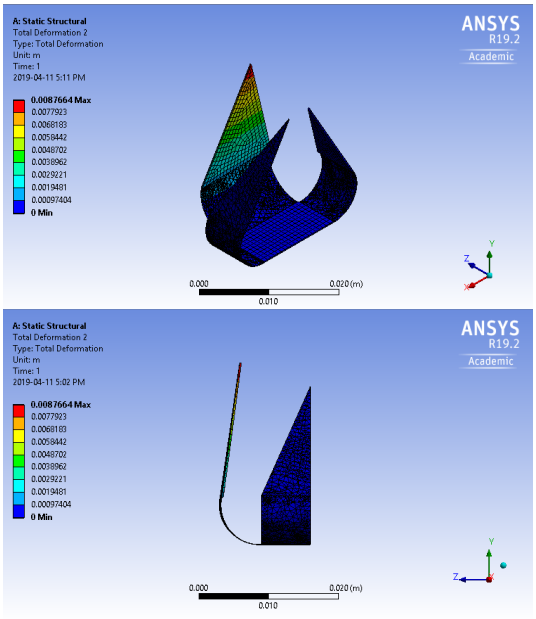

Fig. 7. Arm deformation simulation for micro-gripper with SiO_2 base.

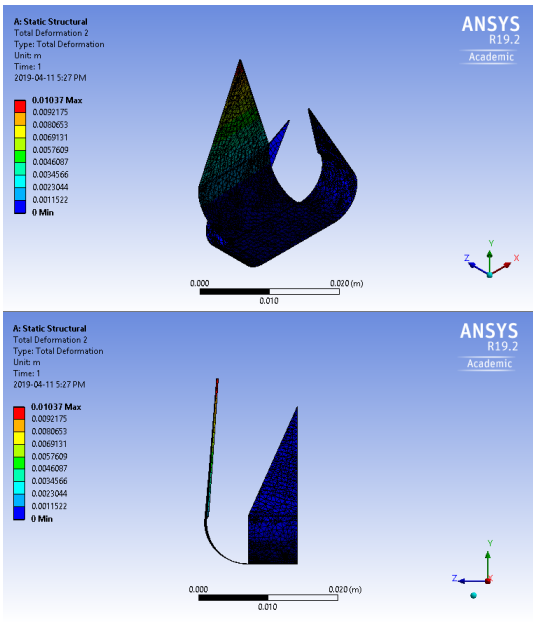

Fig. 8. Arm deformation simulation for micro-gripper with SiO base.

According to the beam bending theorem, the deformation resulted from applied torque

$$\omega = \frac{L^2 T}{2EI} = \frac{L^2 mB}{2EI} \tag{3}$$

,where L is the length of the beam and E is the elastic modulus of material, I is the second moment of inertia, T is the applied torque, m is the magnetic moment of the beam and B is the magnetic flux density. If we assume the magnetic flux density applied at the location is constant, given the fact that elastic modulus is a material property

therefore scale independent, we have the following scaling law for the deflection of the beam

$$\omega \propto \frac{L^2 \times L^3 \times L^0}{L^0 \times L^4} \propto L \tag{4}$$

Since the deformation of the micro-gripper is proportional to the geometry size of the micro-gripper, we expect the real micro-gripper can be open with a permanent magnet to a near 90° bending angle. The size to distance ratio of the permanent magnet used in Magneto-static simulation is $\frac{2}{3}$. Any permanent magnet with a larger ratio can saturate the micro-gripper and open micro-gripper arms by applying magnetic torque.

B. Gazebo Simulation Results

An attempt was made to compare the inverse dynamics calculations in Gazebo, however, there were issues with controlling the robot that prevented us from finding those results and thus only a forward dynamics result is available.

A continuous high-order trajectory was able to smoothly move the micro-gripper as expected in a linear motion. However, an approach to the micro-gripper without causing unintended locomotion is tricky without solving for the desired micro-gripper trajectory first using the Jacobin which maps between the change in the force and torque to the relative position and heading between the micro-gripper and actuating magnet.

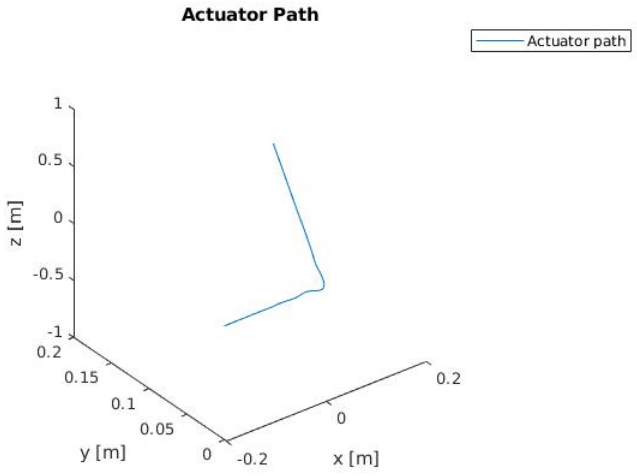

Fig. 9. Position of Actuator relative to initial micro-gripper frame.

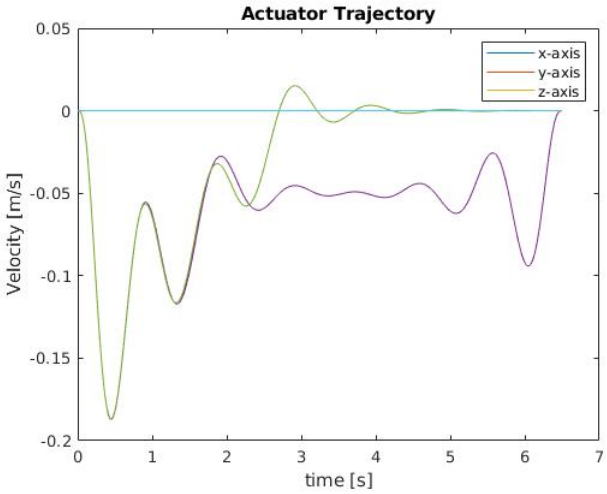

Fig. 10. Velocity of Actuator relative to initial micro-gripper frame.

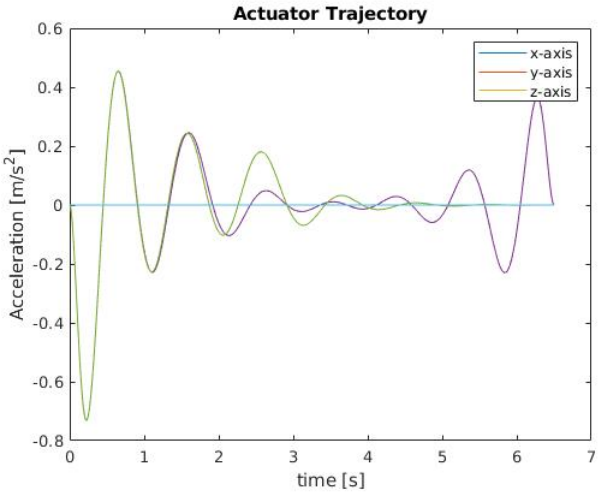

Fig. 11. Acceleration of Actuator relative to initial micro-gripper frame.

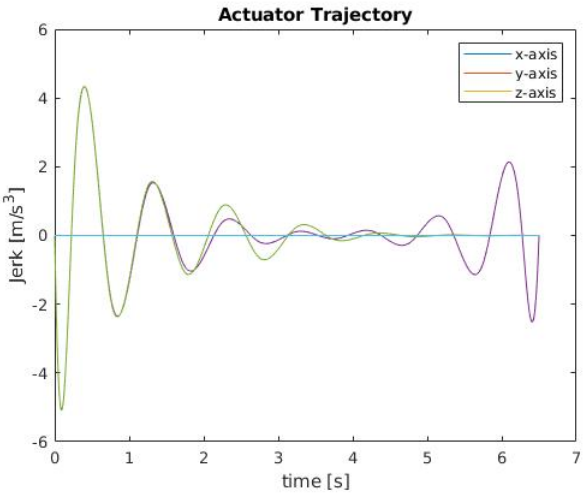

Fig. 12. Jerk of Actuator relative to initial micro-gripper frame.

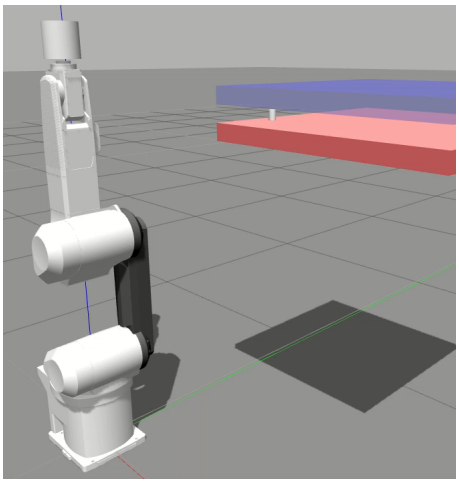

Fig. 13. Robot home pose.

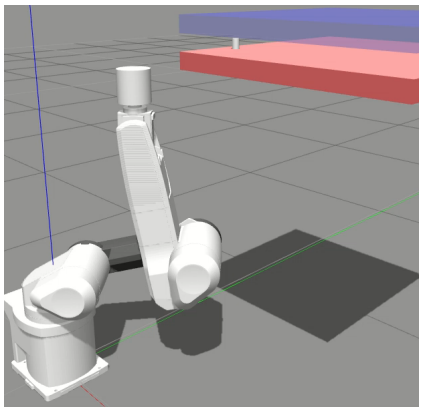

Fig. 14. Trajectory start pose.

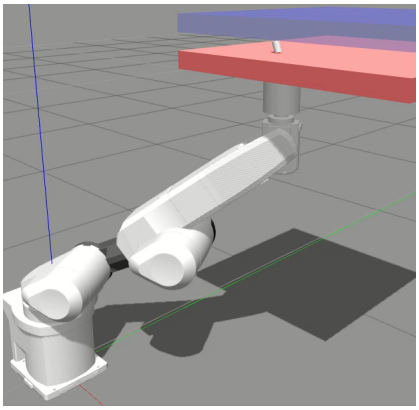

Fig. 15. Trajectory end pose.

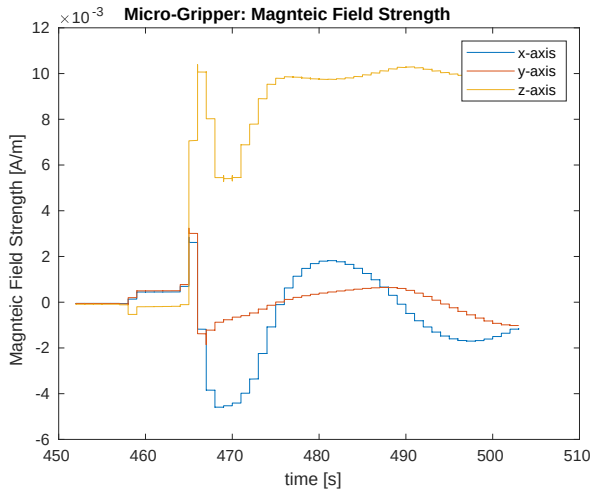

Fig. 16. Magnetic Field Strength on Micro-Gripper.

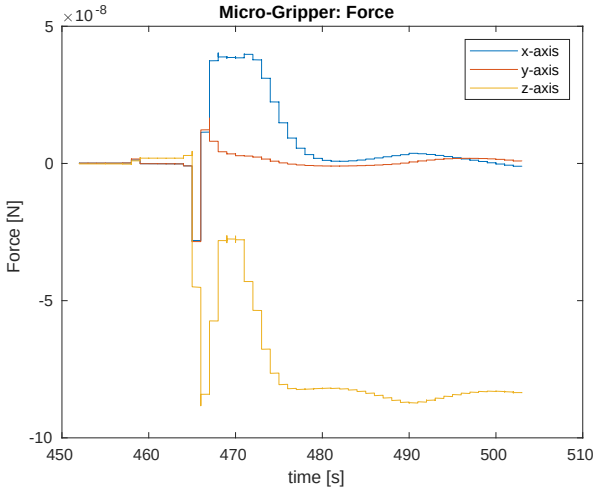

Fig. 17. Force on Gripper.

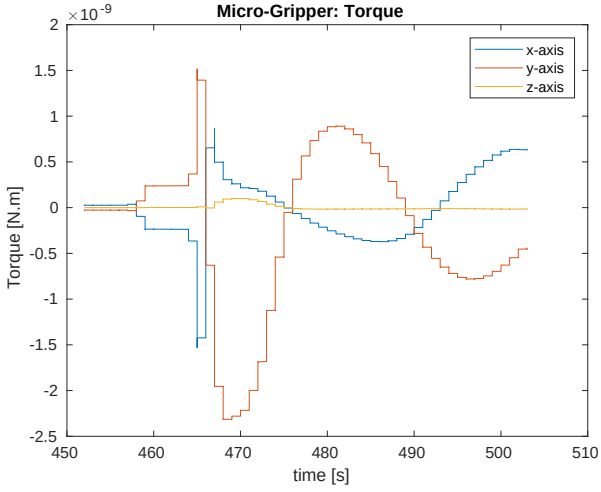

Fig. 18. Torque on Gripper.

V. RECOMMENDATIONS FOR FUTURE WORK

A better mapping of the dynamics with higher degrees of freedom and under multiple actuating magnets should be conducted in gazebo to better control the gripper and accurately reach more of the desired states.

Furthermore, the ANSYS simulation results can be used to determine the constraint on the B-field which is required to keep the gripper open. This can be incorporated with the inverse dynamics as a path planning constraint.

VI. CONCLUSIONS

From the preliminary results derived so far, we expect that the current design of the mobile micro-gripper is feasible. The Gazebo simulations proves the feasibility of micro-gripper control, and the ANSYS simulations demonstrates the potential in inducing actuated function to a soft magnetic micro-gripper. Based on ANSYS simulation, a commercially available permanent magnet is capable of saturating the micro-gripper and generating enough torque to open micro-gripper arms, giving a desired open deformation of the microgripper.

APPENDIX

ACKNOWLEDGMENT

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