ME-436 MICRO/NANO ROBOTICS 26.05.2025

TAKE HOME EXAM

INSTRUCTIONS

You are expected to submit a single report (pdf file) as a group that contains your answers to the following questions. Every group member is expected to answer 2 questions. For example, if your group has 5 members, choose 10 questions. You have 3 hours, i.e. **upload your report on Moodle by noon today** (May 26th). Clearly denote who worked on which questions. You can use any material (images, data, equations, etc.) from the assigned articles, other articles from the literature or webpages as long as they are properly cited in your report. There is no page limit.

QUESTIONS

1. Article 1. The elastic energy storage is performed through beam buckling. By using a beam with bigger dimensions, one can store more elastic energy during the buckling process, resulting in an increase of jump height but also to an increase of embedded mass, which is penalizing for the jump height. Therefore, what is the optimum in terms of beam dimensioning to maximize the jump height? How would the takeoff velocity and escape time of the dynamic buckling cascade robot vary if its scale were further reduced, given that lambda represents the size ratio, with stiffness scaling as lambda and volume (and therefore mass) scaling as lambda^3?

2. Article 2. The article presents that a key innovation for durability was to diverge from biological systems and use a longer hinge to reduce flexural stress. Could this be achieved instead by having a more flexible wing, which may also have the benefit of better energy efficiency through aerodynamics? Figures 3A and 3D demonstrate how the redesigned hinge reduces flexural stress by over 1000 times, but this was achieved by extending the hinge along the entire wing instead of restricting it to a localized flexure. How does the elongated hinge compare with biological resilin-based hinges in insects in terms of flight stability, energy dissipation and load distribution? Could there be a more optimal hinge geometry that balances stress reduction while maintaining aerodynamic efficiency?

3. Article 3. Unlike electromagnetic motors, the electrostatic motor in CoulombFly produces an almost constant torque. How does the electrostatic motor exhibit a nearly constant torque across varying loads, and what underlying physical or electrical mechanisms contribute to this self-regulating behavior? As we can see on video 2 the blades change their electrical sign when they pass an electric brush. How do the number and width of electrode plates affect the efficiency of the electrostatic motor? Is there an optimal combination of electrode plate width and rotor blade count that maximizes torque and rotational speed without excessive energy loss?

4. Article 4. Figure 2c shows a unit cell switching between states in roughly 100 ms, limiting the maximum actuation frequency to about 5 Hz. Why is this frequency limit observed, and which factors—such as redox reaction kinetics, viscous damping from the fluid environment, or mechanical deformation rates—primarily set this operational constraint? What happens if the command delay is lower than the mechanical delays of the structure to change its position? Why is the switching time in both directions identical, although the voltages are not the same? Hinges can move through multiple steps like open, closed, or anything in betwen. Would it be possible to control them to keep a hinge at a specific angle anywhere between 0° and 180°, rather than just flipping between fully open or fully closed?

5. Article 5. How does the microrobot in Figure 2 able to walk and swim, having only one joint and thus being forced into reciprocal motion? How does changing the phase relation between in-plane and out-of-plane magnetic fields control the switch between walking and swimming modes, and how do drag forces influence the maximum actuation frequency? In Movies S1 to S3, locomotion relies on a $\pi/2$ phase shift between B_x and B_z. Why was this exact phase chosen, and is it optimal for the shape? Would non-sinusoidal function improve locomotion?

6. Article 6. The article mentions a magnetic workspace with field strength ranging from 10 to 30 mT in various directions. How is the "magnetic feasible workspace" calculated and why is directional uniformity important for clinical applications? Navion's electromagnets use laminated silicon steel cores. Why is this material preferred over solid ferromagnetic cores in this application, and how does lamination impact the dynamic response of the field during time-varying actuation?

7. Article 7. Authors say that they tried both a highly soft solid wheel and Kirigami wheel, but they retained Kirigami wheel instead of the solid one due to the buckling risk of the wheel under large compression. First, why are Kirigami wheels not subjected to the same buckling risk under the same load? Can you explain how the kirigami wheel structure prevents buckling for rotation under large compression? Why does the thickness-to-diameter ratio of rings (p_t) in the kirigami wheel affect the compressive stiffness of the wheel but not fluctuation rate? The kirigami wheel's normal force (F_n) and fluctuation rate (η_{wheel}) seems insensitive to changes in the diameter ratio parameter (p_d), as shown in Figure S4A. What structural properties of the layered ring design explain this independence from p_d variations?

8. Article 8. Does the size and shape of the orifice influence the entrapment? Why doesn't the bubble escape due to buoyancy forces? What shell thickness to orifice size ratio would optimize the trade-off between bubble stability and propulsion efficiency? The orifices exhibit an arc-like, tangent shape rather than a circular design. What are the specific physical or flow dynamic advantages of this arc-like geometry? It is stated that the placement and size of the orifice ensure asymmetry, which is necessary for propulsion. How was the number of orifices determined? Could we add more holes compared to the existing one while maintaining asymmetry to generate more thrust?

9. Article 9. The article presents a model for the secondary acoustic radiation force acting between two confined oscillating bubbles incorporating a geometric correction coefficient β to account for confinement. Why is the fitting parameter β necessary for confined geometries? What physical factors or phenomena specific to these 3D-printed microactuators, which might not be fully captured by the base theoretical model for secondary forces between ideal bubbles given in Eq. (1), could this parameter β be implicitly accounting for? How does the parameter β, which encodes geometry-dependent acoustic force contributions, scale with the orifice shape and cavity depth?

10. Article 1. Considering the lumped model shown in Figure 6A, what are the parameter conditions and inequality constraints (especially on the acceleration of m_b) required to initiate ghost jumping? The mathematical modeling section uses a simplified lumped mass-spring model to predict the jumping height and velocity of the robots, noting a good agreement between theory and experiment. However, the model breaks down somewhat towards the end of each jump, with the predicted velocity leveling off while the experimentally observed velocity does not. In what ways could the mathematical model be refined or expanded to more accurately capture the complex dynamics of the jumping robot, particularly concerning the ground interaction and energy dissipation during the later stages of the jump?

11. Article 3. The vehicle test was conducted at a sunlight inclination angle of approximately 48° and a natural light intensity of 920 Wm^{-2}. Was the angle of 48° found to be the optimal or most efficient angle, or was this selected due to experimental constraints? How is the performance of the CoulombFly (particularly lift force and potential flight duration) affected by variations in inclination angle and solar irradiance? What would be the critical light intensity threshold below which sustained flight would no longer be possible? The article explains that solar cells are placed underneath the vehicle for mass stability. Why are there only two cells at the front? Why not placing cells all around the MAV for a better center of gravity?

12. Article 8. Why do very small (1 μm) or very large (100 μm) microrobots performs worse than those of intermediate size? How does changing the microbubble diameter influence the resonance frequency and subsequently affect the acoustic streaming patterns around the microrobot? The authors state that reducing bubble size causes the active frequency region to broaden and increases the number of responsive frequencies. Could you clarify the physical mechanisms behind this?