Robotic Flight Inspired by Bat Wings

Niyati Abhijeet Vaidya
Arizona State University
(Student)

Vivek Sunil Kulkarni
Arizona State University
(Student)

Prajjwal Dutta
Arizona State University
(Student)

Yogesh Pradeep Salvi
Arizona State University
(Student)

***Abstract*— This project explores optimized actuation and gait pattern strategies to enhance the locomotion speed and agility of multi-modal robots designed for aerial mobility. Inspired by Palla's long-tongued bat (*Glossophaga soricina*), the research initially focuses on modeling gliding and landing mechanics, leveraging the bat's adaptive wing morphology and precise control enabled by its elastic wing membranes. Following our professor's suggestion, the study later incorporates a flapping mechanism to improve the robot's versatility and maneuverability. The findings contribute to bio-inspired robotics by advancing foldable wing designs and informing the development of agile drones for navigation in cluttered environments, with applications in rescue missions and automated surveys.**

Keywords— Bio-inspired robotics, foldable robotics, adaptive wing morphology, energy-efficient design

I. System Model Definition

This bio-inspired robotics project's system model design aims to create a robotic system that simulates the gliding and flapping motions of the Glossophaga soricina bat species. To maximize performance in terms of agility, stability, and energy efficiency, the main objective is to simulate the robot's dynamic and physical behaviors.

A. *Objective*

The objective of the system model is to optimize the performance, stability, and energy efficiency of the bio-inspired robot by simulating its dynamics and understanding the interactions between its components. The model aims to predict gliding trajectories, aerodynamic forces, and landing impacts, enabling the evaluation of various wing configurations and actuation strategies.

The approach makes it easier to build a robotic system that is precise, efficient, and adaptable by examining how material qualities and control inputs affect system outputs. It also acts as a basis for testing and prototyping, offering vital information on important variables including system inertia, actuator dynamics, and wing size.

B. *Key components*

1) A Wing System: The initial prototypes utilized basic materials such as wax paper for the wing structure. However, the final wing design featured a two-layer lamination composed of a thin vinyl sticker sheet and a flexure material. This advanced design incorporated vein-like structures inspired by bat wings. The advanced design included vein-like structures inspired by bat wings that acted as hinges for flapping and made the wings foldable. This foldability allowed the wingspan to adjust dynamically, improving the robot's agility and adaptability in flight.

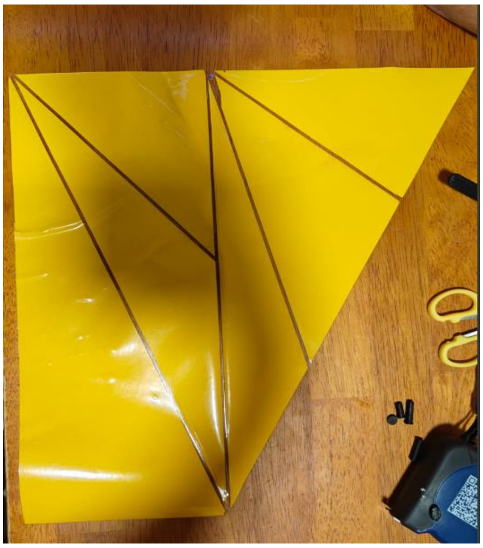

Fig 1 Final wing design

2) Body Structure: This mechanism employs a gear-driven actuation system, converting rotational motion into the movement of connected mechanical links. It utilizes servo motors to achieve multi-link folding, mimicking the dynamic adaptability of bat wings. The actuation, guided by torque and angular speed control ,ensures precise motion and responsiveness. Additionally, experiments on stiffness and compliance optimize the system's load response, with lightweight materials like balsa or flexible silicone membranes enhancing rigidity and precision for efficient performance.

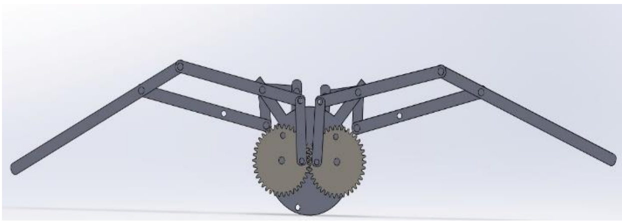

Fig 2 Final body frame

3) Actuators: This is a single-actuator sytem. A servo motor attached on the body structure, in between the two wings is reponsible for flapping of both the wings. The centrally placed position of the motor also helps in maintaining the centre of gravity of the system on the body frame.

4) Power Supply: For our most recent prototype, we have used a direct power supply to the ESP32. In future scope one could also batteries to power the microcontroller and the servo.

II. Optimizing the Design

The design optimization process focuses on improving the robot's gliding efficiency and stability while minimizing energy consumption. The wing design was refined by analyzing the aerodynamic lift-to-drag ratio, which involved testing various wing membrane materials such as silicone and wax paper.

Furthermore, the robot's center of gravity was carefully shifted to balance it and increase its gliding distance. MATLAB and Python simulations were used to assess several design configurations, and the outcomes influenced important choices like choosing lightweight materials and modifying the wingspan for best aerodynamic performance.

A. *Parameter Identification*

In a previous assignment (Parameter Identification), each team member focused on analyzing and identifying one key parameter essential for the project. These parameters included the stiffness of the material, the total body mass and inertia, and the compliance of the materials used.

1) *Stiffness of Material*: The study measured the stiffness of a mechanical system, representing resistance to deformation under force. Six tests were conducted by Prajjwal, starting with the empty chassis and adding components incrementally, culminating in a full system test. A power-law model was applied to force-displacement data using Python tools, revealing the contributions of individual components and their combined impact on structural integrity for design applications.

2) *Material Compliance:* The objective was to identify material parameters, focusing on compliance and weight measurements of components like a cylinder, servo motor, batteries, and an ESP32 breadboard. Using a digital scale and compliance tests, a linear model analyzed displacement under varying loads. Results showed the foam board had higher compliance (0.1578 m/N) than the balsa board, bending more under the same force.

3) *Mass and Inertia of Base:* This section focuses on the mass and moment of inertia of a four-bar bat wing mechanism for precise control and modeling of wing movements. Using a wooden balsa chassis, tests employed a torsional pendulum method to measure oscillation periods at various pivot distances. Python was used for polynomial fitting to analyze data, which was validated against Solidworks simulations. The study demonstrates the practical application of mechanical engineering principles through mathematical modeling and experimental measurements.

4) *Gliding of Base:* This section focuses on determining a glider system's mass and inertia to assess the effects of various membrane materials on its gliding performance. A wooden body with plastic parchment, wax paper parchment, and no membrane were the three combinations that were tried. Free-fall testing and assisted drops were used in the experiments to evaluate glide path, stability, and distance. The results were examined by computing acceleration, velocity, and motion dynamics using a 4th-degree polynomial model. For every arrangement, this assisted in calculating the coefficient of gliding friction and frictional forces. In aeronautical applications, the findings help optimize structural and material selections for effective gliding systems.

B. *Mujoco Models*

This project involves simulating and visualizing a hierarchical mechanical system with articulated joints using the MuJoCo physics engine. The model includes interconnected rigid body-controlled actuators, creating dynamic motion. A custom controller modulates joint positions based on time-dependent sine functions, demonstrating precise control and coordination. The simulation, rendered at 800x600 resolution, showcases mechanical behavior through realistic physics and high-quality visualizations. The frames are compiled into an animated GIF, providing an interactive and illustrative representation of the system's dynamics, ideal for analyzing kinematics and actuator performance.

1) *Code Walkthrough:*

a) Model Definition: The mechanical system, defined in an XML template, includes hinged joints, rigid bodies, and actuators driving sinusoidal motion. Visual properties and physical parameters ensure realistic simulation dynamics.

b) Simulation and Control: The system uses a custom controller to generate sinusoidal joint motions based on parameters like amplitude and frequency. The simulation advances using MuJoCo, updating the system state iteratively.

c) Visualization and Output: Frames rendered during the simulation are compiled into an animated GIF, providing a dynamic visualization of the system's motion for analyzing kinematics and actuator performance.

```xml
<mujoco>
  <visual><global offwidth = "{width}" offheight="{height}" /></visual>
  <option gravity = "0 0 -9.81"><flag gravity = "disable" /></option>
  <option timestep = "0.001" />
  <option><flag contact = "enable"/> </option>
  <compiler angle = "degree" />
  <worldbody>
    <light name="light1" pos="0 0 1"/>
    <body name = "A" pos = "0.05 0 .5" axisangle = "0 1 0 0">
      <joint name = "j1" type = "hinge" axis = "0 1 0" pos = "0 0 0" stiffness = "10" damping = "1" />
      <geom type = "box" size = "1.25 .05 .05" pos = "1.25 0 0" rgba="1 0 0 1" mass = "1" />
      <inertial mass = "1" diaginertia="1 1 1" pos = ".5 0 0" />
       <body name = "B" pos = "1 0 0" axisangle = "0 1 0 0">
        <joint name = "j2" type = "hinge" axis = "0 1 0" pos = "0 0 0" stiffness = "10" damping = "1" />
        <geom type = "box" size = "2.0 .05 .05" pos = "3.4 0 0" rgba="0 1 0 1" mass = "1" />
        <inertial mass = "1" diaginertia="1 1 1" pos = ".5 0 0" />
      </body>
    </body>
    <body name = "C" pos = "-0.05 0 .5" axisangle = "0 1 0 0">
      <joint name = "j3" type = "hinge" axis = "0 1 0" pos = "0 0 0" stiffness = "10" damping = "1" />
      <geom type = "box" size = "1.25 .05 .05" pos = "-1.25 0 0" rgba="1 0 0 1" mass = "1" />
      <inertial mass = "1" diaginertia="1 1 1" pos = ".5 0 0" />
       <body name = "D" pos = "-1 0 0" axisangle = "0 1 0 0">
        <joint name = "j4" type = "hinge" axis = "0 1 0" pos = "0 0 0" stiffness = "10" damping = "1" />
        <geom type = "box" size = "2 .05 .05" pos = "-3.4 0 0" rgba="0 1 0 1" mass = "1" />
        <inertial mass = "1" diaginertia="1 1 1" pos = ".5 0 0" />
      </body>
    </body>
    <body name = "E" pos = "0 0 0.1" axisangle = "0 1 0 0">
      <joint name = "j5" type = "hinge" axis = "0 1 0" pos = "0 0 0" stiffness = "10" damping = "1" />
      <geom type = "box" size = ".05 .05 3" pos = "0 0 3" rgba="1 0 0 1" mass = "1" />
      <inertial mass = "1" diaginertia="1 1 1" pos = "0 0 0" />
    </body>
    <!--<body name = "floor" pos = "0 0 0">
    <geom pos="0 0 0" size = "5 5 0.05" type = "plane" rgba = "0 0 1 1" />
    </body> -->
    <camera name="custom_view" pos="0 -1 0.5" euler="0.5 0 0"/>
  </worldbody>
  <actuator><position name = "motor1" joint="j1" kp="100"/></actuator>
  <actuator><position name = "motor2" joint="j3" kp="-100"/></actuator>
</mujoco>
```

Fig 3 XML of final design

C. Kinematics

The code simulates and analyzes the kinematics of a four-bar linkage mechanism using symbolic computation, optimization, and visualization. It models the system's geometric constraints to ensure closure and calculates the positions, velocities, and dependencies of links in the mechanism. By formulating the problem as an optimization task, the code determines valid angular configurations for different linkage designs while minimizing constraint violations. Jacobian matrices are computed to analyze velocity propagation and dependencies between independent and dependent variables. The results are visualized by plotting the linkage configurations and the velocity vectors of key points, offering insights into the mechanism's motion and behavior.

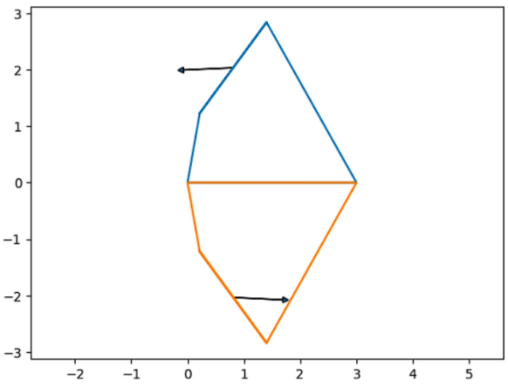

Fig 4 Kinematics model results

D. Final design

After analyzing the parameters and kinematic solutions from Mujoco and Solidworks simulations, we concluded that the frame needed a sturdy material to support both itself and the electrical components. Following a discussion with the professor, it was recommended to incorporate a flapping mechanism in addition to the base's gliding feature.

Based on this suggestion, we modified our design to incorporate a gear-driven flapping mechanism. The frame material was changed from balsa wood to 3D-printed PLA parts. This adjustment was necessary as the earlier balsa wood frame could not support the gear mesh and broke under minimal actuation. Additionally, the balsa wood frame lacked the strength required to facilitate flapping movements or adequately support the wings during operation.

III. Manufacturing

A. Initial Prototype

1) *Base Model:* The base model for this was designed with a simple 4-bar mechanism in mind. The initial model was a Four bar mechanism which was not intended to flap but was focused on changing the wing length using the motor and the four bar mechanism. We intended to change the link lengths to change the wingspan and check the gliding range in three different wingspan positions (Fully open, Partially Open and Fully closed). We have developed a CAD model for this model. Here we used 3 different kinds of materials for making the design. Namely, Foam sheets, Balsa Boards and 3D printed PLA.

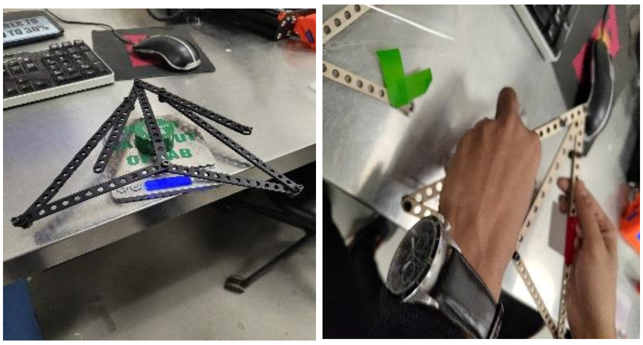
Fig 5 Prototype of Foam(a) and Balsa board(b)

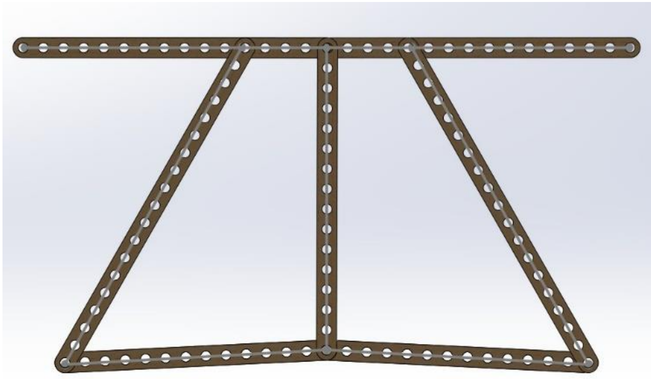
Fig 6 Initial Prototype CAD model

2) *Wing Material*: In this prototype we have used 2 kinds of material for testing of the wings. First was a kitchen paper sheet and another was a clear myler sheet. After testing both of them for the glider we chose to go with the myler sheet for gliding using the gliding experiment for parameter identification.

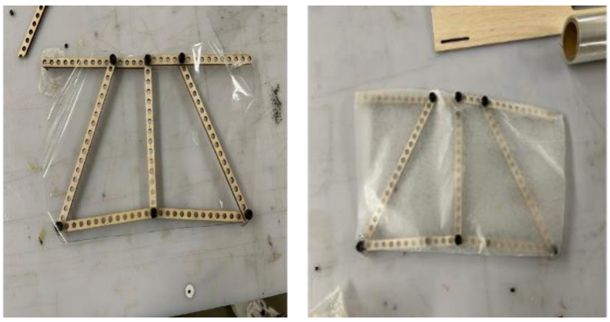
Fig 7 Different wing materials

B. Final Prototype

1) *Base Model:* After showing the intial prototype to professor he gave us some input regarding the model and suggested some changs:

a) The model has some kind of flapping mechanism which can use the force generated through the 4 bar mechanism

b) Implement the lamination techniques which was the part of the course.

Thus, we came up with a improved mechanism to incorporate both the changes. We changed our gliding mechanism to a flapping mechanism of the bat. We made a CAD model for that and as the mechanism was bigger than the previous prototype in size. From the experience of the previous prototype with the balsa board which is very brital we decided to go with the 3D printed links for the structure. This made our model much robust and helped us to implement the 3D printed gear mesh which was a problem for the first prototype as well.

c) Wing Material: The first layer of the mechanism was fabricated using vinyl film. This vinyl film features an adhesive backing, which simplified the assembly process. The desired shape was first cut out from the vinyl film. After removing the backing, the flexure material was directly attached to the adhesive side of the vinyl film. Once the flexure material was securely in place, any excess material was trimmed to finalize the mechanism.

Fig 8 Final prototype

IV. Experimental Validation and Analysis

1) Validation of Stiffness of Material l: The stiffness of the mechanical system was experimentally measured to evaluate its resistance to deformation under force. Incremental tests were performed, beginning with an empty chassis and progressively adding components until the system was fully assembled. A power-law model was applied to the force-displacement data, revealing the contributions of individual components to overall structural integrity. The analysis provided insights into the role of stiffness in optimizing the design for enhanced durability and performance.

2) Analysis of Material Comliance: Material compliance, defined as the deformation under applied force, was analyzed for various components such as cylinders, servo motors, batteries, and ESP32 boards. Using a digital scale and compliance tests, the study revealed that foam boards exhibited higher compliance values compared to balsa boards, indicating a greater degree of flexibility under identical loads. This analysis was critical in choosing appropriate materials for balancing structural rigidity with adaptability.

3) Evaluation of Gliding Dyanmics: The gliding performance of the robot was evaluated using various wing membrane materials, including plastic parchment, wax paper, and an unmembraned frame. Free-fall and assisted drop tests were conducted to measure parameters such as glide path, stability, and distance. A 4th-degree polynomial model was applied to analyze motion dynamics, calculating acceleration and velocity profiles. The experiments highlighted the impact of different materials on gliding efficiency, aiding in the selection of optimal configurations for improved performance.

4) Kinematics Analysis with MuJoCo Models: Using the MuJoCo physics engine, a hierarchical mechanical system with articulated joints was simulated to analyze the dynamics of flapping and gliding motions. A custom controller governed joint positions using time-dependent sine functions, enabling precise control and coordination. The results were rendered into an animated GIF, visually demonstrating the system's behavior under realistic physics conditions. This simulation provided valuable insights into kinematic performance and actuator dynamics.

5) Validation of Wing Design and Dynamics: The wing design was validated through extensive kinematic modeling and material testing. A two-layer laminated structure using vinyl film and flexure material was developed for improved aerodynamic efficiency. The combination of advanced wing materials and a gear-driven flapping mechanism was rigorously tested to ensure robustness and adaptability. These experiments validated the dynamic stability and agility of the robot in both gliding and flapping modes.

6) Impact of Frame Material and Design: The transition from balsa wood to 3D-printed PLA parts for the frame was validated by stress testing and dynamic simulations. The 3D-printed design offered enhanced durability and supported complex mechanisms like the gear mesh for flapping. The robustness of the new frame material was tested under various loading conditions, confirming its suitability for both static and dynamic operations.

7) Final Prototyping and Refinement: The final prototype incorporated feedback from initial experiments, including the addition of a flapping mechanism and advanced lamination techniques. Vinyl films with adhesive backings were used to fabricate the wings, ensuring precision and ease of assembly. The final design underwent iterative testing to confirm its structural and functional integrity, paving the way for further optimization and real-world applications.

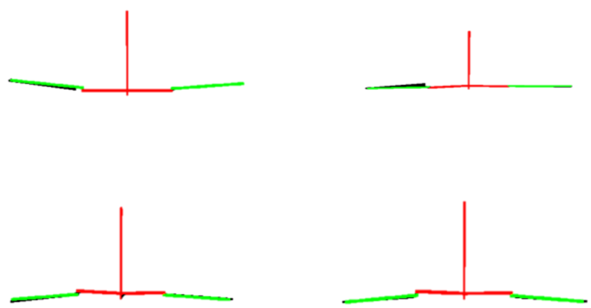

Fig 9 MuJoCo simulation of Wing flapping

V. Results

The results of this project, both simulated and experimental, align closely with expectations for a physical device due to the thoughtful design choices and validation methodologies implemented. The PLA-based 3D-printed structure provided a robust and lightweight frame, essential for supporting the gear-driven flapping mechanism and dynamic wing movements. The use of vinyl film and flexure material for the wings successfully mimicked the bat-inspired adaptive morphology, balancing aerodynamic performance and structural stability. Simulations of the wing dynamics and four-bar mechanism accurately predicted key performance metrics such as gliding stability, range, and flapping efficiency.

Experimentally, the flapping mechanism delivered consistent wing motions with minimal deviations, validating the model's kinematics. The gliding and flapping tests demonstrated stability and controlled motion, supported by material stiffness and appropriate weight distribution. These outcomes align well with physical expectations, as the PLA structure, servo motor dynamics, and wing material properties closely resemble conditions in real-world robotic applications.

Potential deviations between simulations and physical performance are minimal, largely attributed to the high-fidelity modeling in tools like MuJoCo and SolidWorks. The inclusion of real-world parameters, such as material compliance, mass distribution, and joint friction, in the simulations contributed to this alignment. However, minor discrepancies could arise from factors like unaccounted environmental influences (e.g., air currents during testing) or slight manufacturing imperfections in the 3D-printed parts. Overall, the results strongly indicate that the designed prototype will perform reliably under physical conditions, underscoring the validity of the design and analysis process.

VI. Future Scope

Though our project has a proper working prototype of the flapping wings of the bat it still has several scopes of improvement. The main issue for this system is that the simulation and the real prototype are not completely digital twins. We need to first find a way to import the real CAD model to the mujoco instead of box representation for exact replication of the real system.

Furthermore, the power provided to the wings can also be improved so that it can generate enough force to move forward while flapping the wings. Finally, the model fitting can be improved while parameter identification with improved algorithms to calculate closest parameters to the real-world system.

VII. Video Link of the Presentation

Link to final video

References

[1] Woodward MA, Sitti M. MultiMo-Bat: A biologically inspired integrated jumping–gliding robot. The International Journal of Robotics Research. 2014;33(12):1511-1529. doi:10.1177/0278364914541301

[2] A. Ramezani, X. Shi, S. -J. Chung and S. Hutchinson, "Bat Bot (B2), a biologically inspired flying machine," 2016 IEEE International Conference on Robotics and Automation (ICRA), Stockholm, Sweden, 2016, pp. 3219-3226, doi: 10.1109/ICRA.2016.7487491.

[3] A. Ghanbari, E. Mottaghi and E. Qaredaghi, "A new model of bio-inspired bat robot," 2013 First RSI/ISM International Conference on Robotics and Mechatronics (ICRoM), Tehran, Iran, 2013, pp. 403-406, doi: 10.1109/ICRoM.2013.6510141

[4] A. J. Bergou, S. Swartz, K. Breuer and G. Taubin, "3D reconstruction of bat flight kinematics from sparse multiple views," 2011 IEEE International Conference on Computer Vision Workshops (ICCV Workshops), Barcelona, Spain, 2011, pp. 1618-1625, doi: 10.1109/ICCVW.2011.6130443.

[5] Anders Hedenström, L. Christoffer Johansson; Bat flight: aerodynamics, kinematics and flight morphology. J Exp Biol 1 March 2015; 218 (5): 653–663. doi: https://doi.org/10.1242/jeb.031203

[6] OpenAI, personal communication, December 10, 2024