MIDTERM EXAMINATION

Evolutionary Algorithm Generator for Controlling Strategies of a Batbot

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1 Introduction

In the evolving landscape of robotics and autonomous systems, the quest to develop innovative control algorithms for complex or challenging-to-simulate systems has gained substantial momentum. This research delves into this burgeoning field by focusing on the development of a bat-inspired robot, hereafter referred to as "Batbot." The core objective is to train the Batbot to hover using the sophisticated genetic algorithm known as Covariance Matrix Adaptation (CMA). This endeavor not only aims to advance our understanding of autonomous flight in robotics but also holds the potential to pioneer new pathways in controlling algorithms for intricate systems.

The significance of this research lies in its capacity to bridge the gap between theoretical algorithmic control and practical application in physically demanding environments. The Batbot, with its intricate flight mechanics and dynamic response system, presents an ideal testbed for exploring the feasibility of applying advanced genetic algorithms in real-world scenarios. The challenge is magnified due to the need to synchronize a multitude of technologies to create a conducive learning environment for the Batbot.

Initial attempts to develop this system encountered significant hurdles. The use of the STM32 microprocessor, seen in figure 1, while offering a robust platform, introduced complexities due to its reliance on C++, a low-level programming language. This complexity was compounded by issues encountered in wireless communication. Trials with a Bluetooth module were met with reliability issues, and the use of an ESP8266 Wi-Fi module necessitated the additional complexity of incorporating a modem, found in figure 2. Further, the initial choice of force sensors, seen in figure 3 – load sensors with multiple moving parts – introduced data inaccuracies or of low precision, as seen in 4. These inaccuracies were exacerbated by mechanical stresses in the system, leading to inconsistent readings influenced by the initial loads and the tightness of the screws in the assembly.

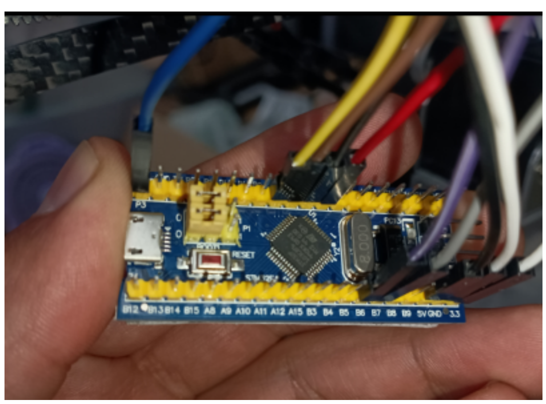

Figure 1: STM32

However, after several months of rigorous trial and error, a more effective solution emerged. The transition to a Pyboard, found in figure 5 utilizing MicroPython, offered a more user-friendly coding environment and enhanced reliability. This shift significantly

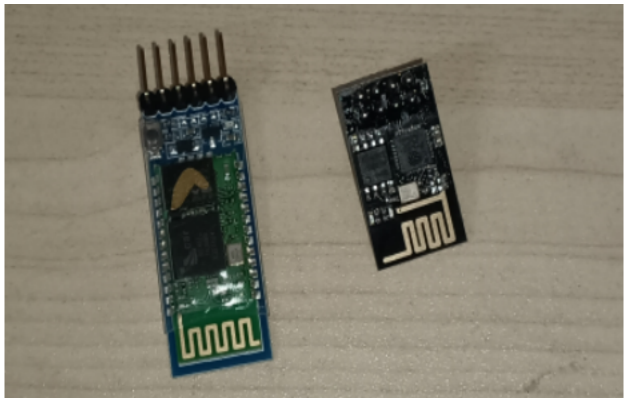

Figure 2: Bluetooth and ESP8266 Modules

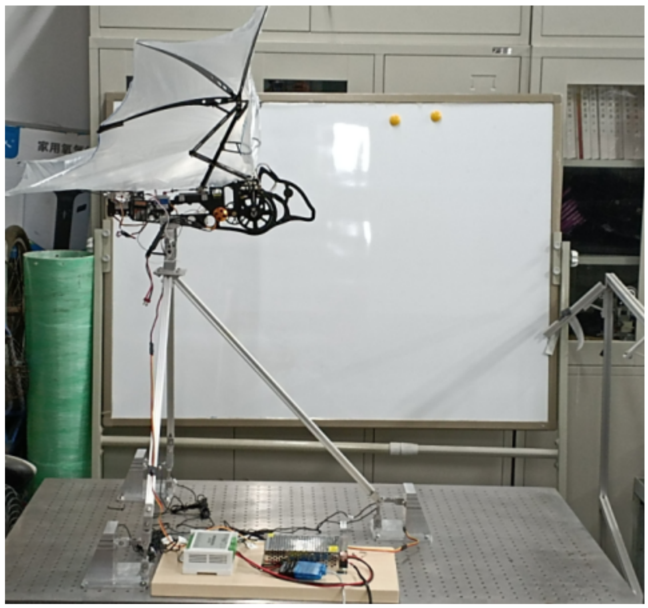

Figure 3: Previous Static Bench

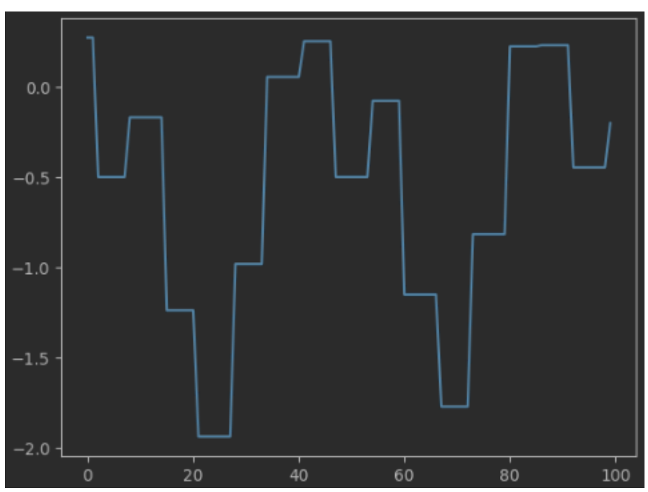

Figure 4: Bad data from previous static bench

streamlined the development process. In tandem, the adoption of a wireless UART, figure 6, module provided a robust and reliable means for wireless communication. Perhaps most crucially, the replacement of the initial force sensors with a 6-axis sensor, as seen in figure 7, – devoid of moving parts – markedly improved data precision. This sensor not only yielded more accurate readings of the three forces and three torques but also laid the groundwork for more sophisticated future analyses, as seen in figure 8. The new static test-bench can be seen in the figure 9.

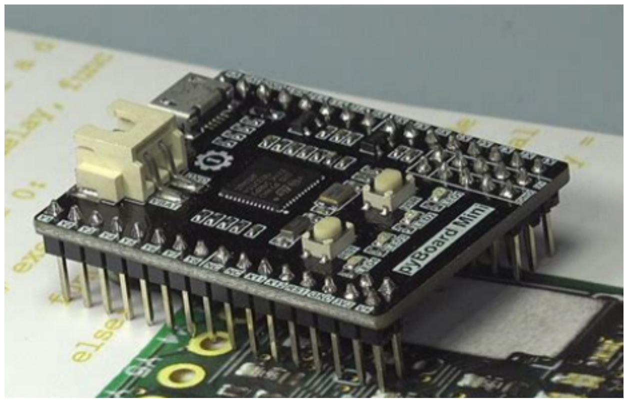

Figure 5: PyBoard

Figure 6: Wireless UART Module

The culmination of these developments heralds a new phase in the Batbot project, opening promising avenues for the application of genetic algorithms in complex robotic systems.

2 Optimization Algorithm

The primary goal of this research is to optimize the movement of the Batbot's hind-legs to generate maximum lift. This optimization is critical in achieving stable and efficient hovering for the Batbot.To accomplish this, the movement of the Batbot's hind-legs has been parametrized as an elliptical motion. This approach requires the optimization of five key parameters, seen in figure 10: the center of the ellipse (defined by x and y coordinates), the amplitude of the ellipse along the x and y axes, and the shape/direction of the ellipse.

Figure 7: 6 Axis Sensor

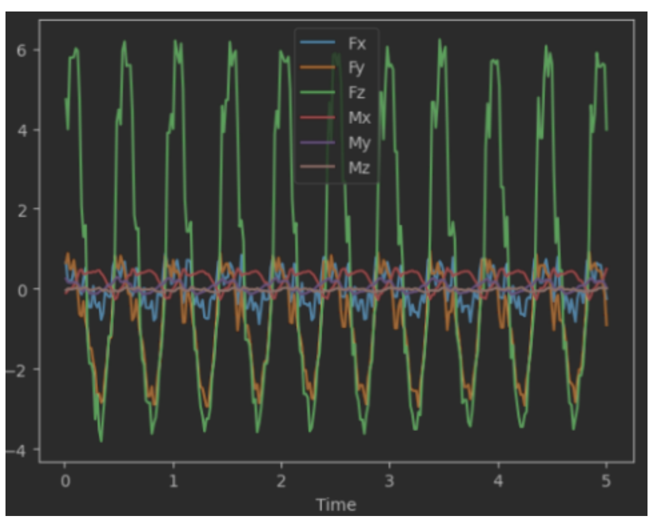

Figure 8: Good quality data of new sensor

Figure 9: Static Test-Bench

Additionally, the leg movement is intricately linked to the angle of the wing, which is monitored using a magnetic angle encoder. This coupling is crucial for coordinating the overall motion of the Batbot.

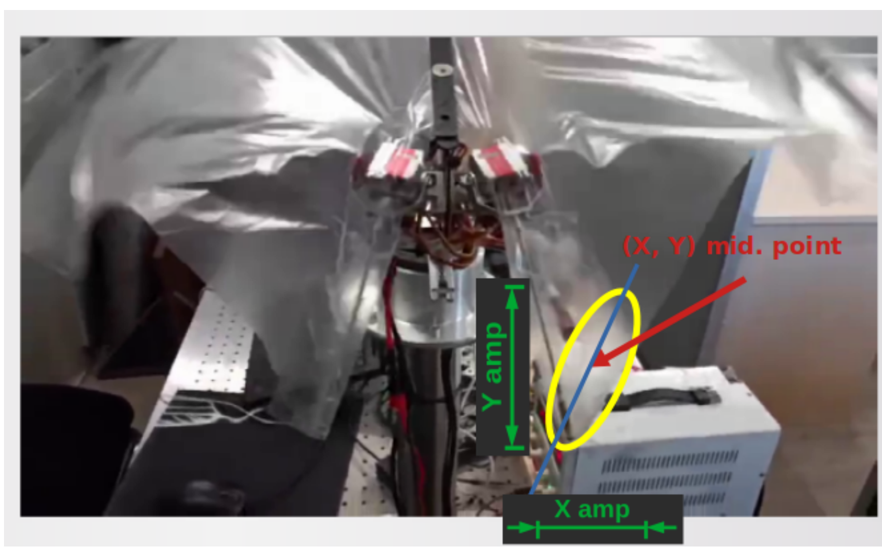

Figure 10: Hind-leg parametrization

2.1 Workflow of a Test

The testing process is structured as follows, a diagram for better understanding can be found in figure 12. The result of a test can be seen in figure 11, were on the leftside we can see the forces in z and y directions as well as the peaks used to analyze only complete cycles, on the right side we can see the same information but using different axis, also the resulting average force is shown:

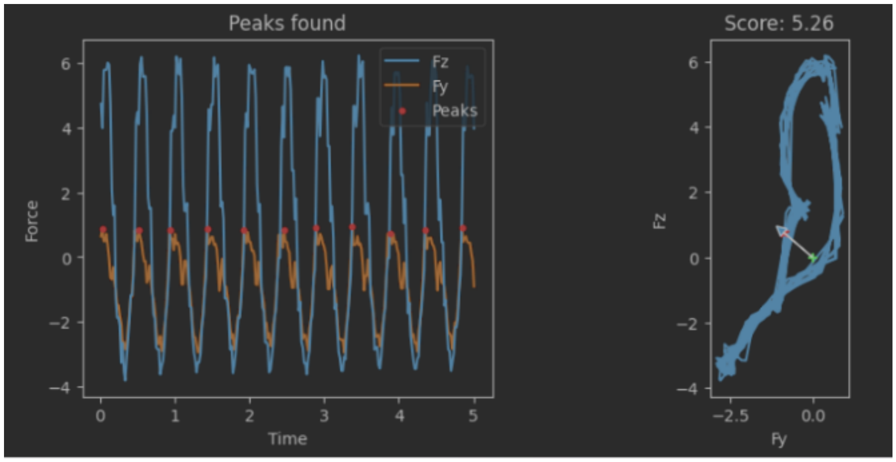

Figure 11: Test result

1. **Initiation:** A Python script initiates the test by sending a proposed solution (the values for the five parameters) to the Batbot via wireless UART communication.
2. **Execution:** The Batbot then executes these movements. During this phase, the integrated sensor gathers data on the torques and forces generated by the movement.
3. **Data Transmission and Analysis:** The collected data is transmitted back to the computer via USB using the ModBus Protocol. The Python script processes this data, focusing on identifying peaks to isolate complete cycles. It then calculates the average force generated during these cycles.
4. **Scoring:** The effectiveness of each test is quantified by calculating the Euclidean distance between the average force generated and the Batbot's weight (670 grams). This score serves as the basis for evaluating the success of each parameter set.

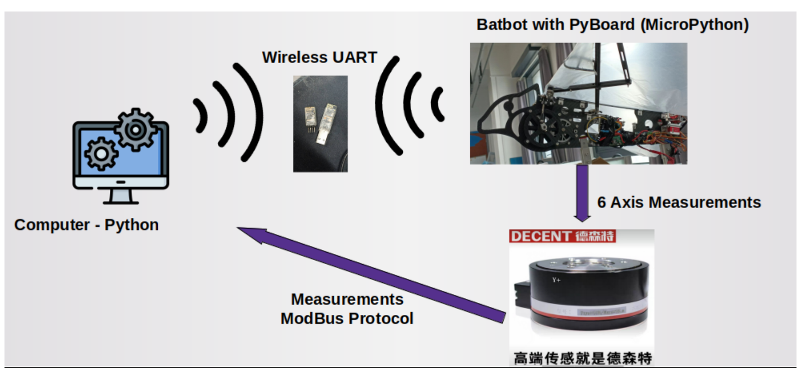

Figure 12: Hardware

2.2 Optimization Process

With a clear understanding of the testing workflow, the overall optimization process using the Covariance Matrix Adaptation (CMA) algorithm can be explained:

1. **Generation of Solutions:** The CMA algorithm initially generates ten different solutions (sets of the five parameters).

2. **Testing and Scoring:** Each of these solutions is tested sequentially using the workflow described above. The score for each solution is calculated based on its performance.

3. **Algorithm Optimization:** Using the scores obtained from these tests, the CMA algorithm undergoes an optimization process. This process involves refining the algorithm based on the performance data to generate ten new, improved solutions for the subsequent generation.

4. **Iterative Improvement:** This cycle of generating solutions, testing, scoring, and refining the algorithm is repeated iteratively. The process continues until the algorithm converges, indicating that the optimal parameters for the hind-leg movement have been identified.

2.3 Results of the Optimization

2.3.1 Data Quality and Learning Progress

The optimization process for the Batbot's hind-leg movements yielded high-quality, precise, and reliable data. This robust data quality was instrumental in accurately calculating the scores necessary for the optimization process. A significant observation was made after just 20 generations of the algorithm: the scores consistently decreased, indicating clear learning, found in figure 13.

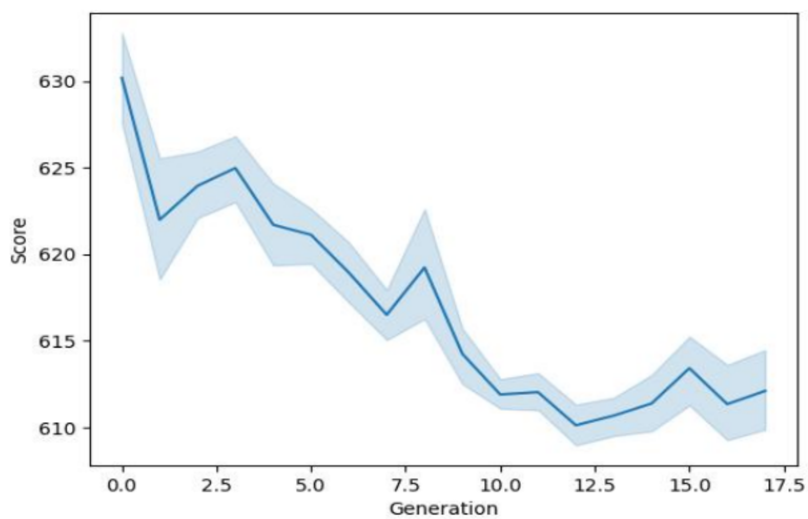

Figure 13: Learning progress

2.3.2 Analysis through Parallel Coordinate Plot

One of the most insightful analyses was conducted using a parallel coordinate plot. This type of plot is particularly effective in visualizing high-dimensional data. In a parallel coordinate plot, each parameter is represented by a vertical line, and individual solutions are displayed as lines crossing these vertical lines, figure 14. The position where a line crosses a vertical line indicates the value of that parameter for the given solution. In our specific analysis, lines in the plot were color-coded: yellow lines represented solutions with better scores, indicating more effective parameter combinations for the Batbot's hovering capability, while blue lines indicated worse scores. This color-coding further enhanced the plot's utility in quickly identifying patterns and correlations across multiple dimensions. It made it easier to distinguish optimal solutions that stood out in the parameter space. The plot for our data revealed a distinctly effective solution, clearly differentiated from the rest by its color, signifying its superior performance.

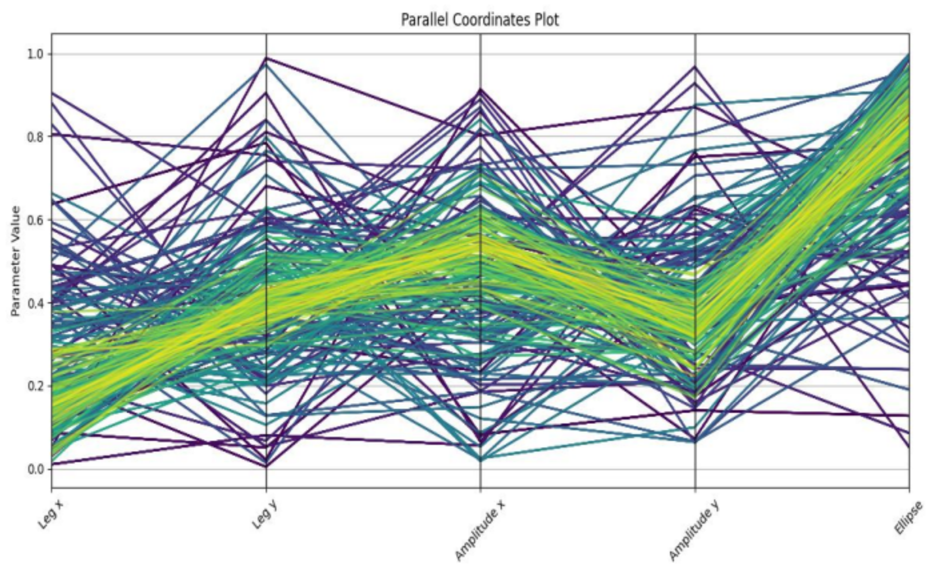

Figure 14: Parallel Coordinate Plot

2.3.3 Encounter with Physical Limitations

Despite the algorithm's initial success, we encountered a stagnation in learning, indicating that the algorithm had possibly reached the physical limitations of the Batbot's current design. To understand this plateau, we analyzed the relationship between the force and lift generated by the Batbot and its flapping frequency, as seen in figure 15. Intriguingly, even at a high flapping frequency of nearly 5 Hz, the maximum force exerted was only 2.4N, significantly lower than the required 6.7N for effective hovering.

2.3.4 Insights from Forward Flight Comparison

This result was particularly surprising given previous tests where the Batbot achieved lift in forward flight at around 4 Hz. Upon further investigation, we realized that in forward flight, the airflow over the wings creates lift, similar to an airplane wing. However, in hovering, where the Batbot remains static, this aerodynamic lift is absent. This distinction was crucial in understanding the limitations faced during the hovering tests.

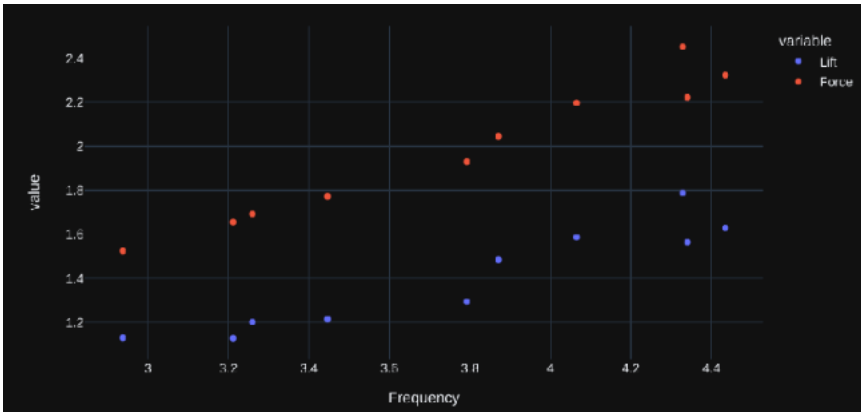

Figure 15: Frequency Analysis

2.4 Conclusions

The conclusion drawn from these results is that while the algorithmic optimization was successful within the mechanical constraints of the Batbot, the design of the Batbot itself requires enhancement to achieve the desired hovering capability. The current design does not fully capitalize on the aerodynamic principles that assist in lift during forward motion. This realization points towards the necessity for a mechanical redesign of the Batbot, aiming to incorporate features that can generate sufficient lift even in a static hover. This upgrade will be pivotal in harnessing the full potential of the algorithmic advancements and achieving the ultimate goal of efficient and stable hover in Batbot.

3 Batbot Upgrade

The initial design of the Batbot, while innovative, encountered several significant challenges that limited its performance, particularly at higher operational velocities. One of the primary issues was the use of a single gear to drive the wing movements. This design choice led to two major problems:

1. **High Stress on Gear Teeth:** The single-gear mechanism bore the entire load of wing movement, leading to excessive stress on the gear teeth. This stress often resulted in damage when the Batbot operated at high velocities, compromising the durability and reliability of the system.

2. **Unbalanced Force Distribution:** The single gear also contributed to an uneven distribution of forces and weight across the Batbot's structure. This imbalance was detrimental to both the efficiency of the Batbot's movements and the longevity of its components.

To overcome these challenges, a series of upgrades were introduced to the Batbot's design:

1. **Dual Gear System:** The most significant change was the replacement of the single gear system with a dual gear mechanism. This new setup, featuring one gear for each wing, dramatically improved the Batbot's performance. By distributing the load

more evenly, the dual gears reduced the stress on individual gear teeth, significantly lowering the risk of damage during high-speed operation.

2. **Increased Flapping Amplitude:** The amplitude of the wing flapping was increased to enhance the Batbot's aerodynamic lift. This modification was crucial in improving the Batbot's ability to achieve and maintain stable hovering.

3. **Upgraded Motor:** To accommodate the increased demands of the new wing movement, the motor was upgraded to a more powerful 100W motor. This upgrade provided the Batbot with the necessary power to operate the wings efficiently, especially at higher flapping frequencies.

4. **Addition of a 50 Amp Electronic Speed Controller:** To ensure that the system had access to sufficient current for its operations, a 50 amp electronic speed controller was incorporated. This addition was pivotal in managing the power supply to the upgraded motor, ensuring smooth and responsive control over the wing movements.

These upgrades, found in figure 16, collectively addressed the key limitations of the previous design, paving the way for a more robust, efficient, and reliable Batbot. The introduction of a dual gear system, in particular, marked a significant step forward in the mechanical design, allowing for higher operational speeds without compromising the integrity of the system. With these enhancements, the Batbot is now better equipped to explore the boundaries of autonomous flight and contribute to the broader field of robotic design and control.

Figure 16: Batbot upgrade

4 Dynamic Test-bench Analysis

To comprehensively evaluate the performance of the upgraded Batbot, a dynamic test bench was developed. This innovative testing apparatus offers several key advantages over the static test scenarios previously employed. The dynamic test bench is centered around a 6-axis sensor mounted to the ceiling. Suspended from this sensor is an elastic string, at the end of which the Batbot is attached. This setup is meticulously designed to simulate a more realistic hovering environment for the Batbot, providing a host of benefits. First of all, it allows for realistic hovering simulation. Unlike static tests, the dynamic test bench allows the

Batbot to move freely in space. This freedom is crucial for accurately assessing the Batbot's hovering capabilities, as it closely mimics the conditions the Batbot would encounter in real-world applications. Another major advantage is the safety and repeatability of experiments. The elastic string not only facilitates movement but also ensures the safety of the Batbot during testing. It prevents the Batbot from drifting too far or colliding with other objects, thus enabling repeated experiments without the risk of damage.

4.1 Testing Procedure and Data Analysis

The testing process on the dynamic test bench works as follows:

1. **Hovering Test:** If the Batbot hovers effectively, the elastic will pull it towards a central position. This state indicates a successful hover with minimal external forces acting on the Batbot.

2. **Force Measurement:** In instances where the Batbot fails to hover effectively, a force will be exerted on the elastic string, which is then measured by the 6-axis sensor. This force provides crucial data on the Batbot's performance.

3. **Calculation of Resulting Force and Position:** By knowing the forces acting in all three axes, the resultant force exerted by the Batbot can be calculated. Additionally, utilizing the known elastic constant of the string and applying Hooke's Law, the position of the Batbot can also be determined.

This dynamic test bench , seen in figure 17 represents a significant advancement in testing the Batbot's capabilities. By offering a more realistic and safe testing environment, it allows for a more accurate assessment of the Batbot's performance in hovering. The ability to calculate both the force exerted and the Batbot's position provides a comprehensive understanding of its dynamics, crucial for further optimization and development. As such, this test bench is an invaluable tool in refining the Batbot's design and enhancing its functionality.

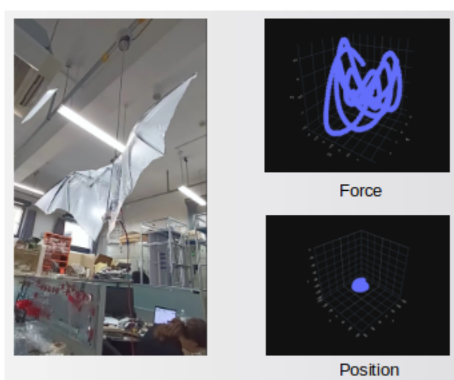

Figure 17: Dynamic test-bench and measurements

4.2 Results of Dynamic Test-bench Analysis

The application of the dynamic test bench in evaluating the upgraded Batbot provided enlightening results, particularly concerning its ability to hover. A key observation was made regarding the force exerted in the vertical (z) direction. During the tests, it was observed that the force in the z-direction exhibited a clear tendency to approach zero, as seen in figure 18. This is a significant finding, as it indicates a state of equilibrium where the upward force generated by the Batbot's wings effectively counterbalances its weight.

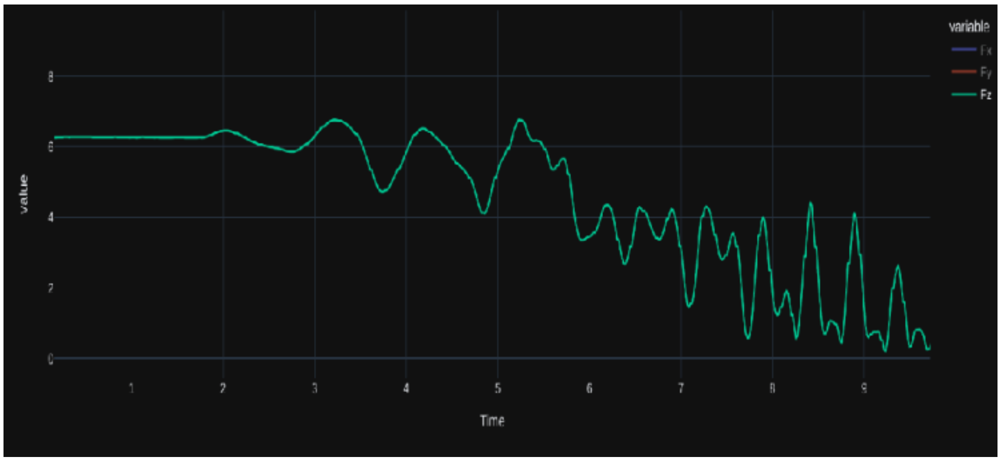

Figure 18: Measurements that show hovering capabilities

The tendency of the z-direction force towards zero is a strong indicator that the modifications made to the Batbot, including the dual gear system, enhanced flapping amplitude, upgraded motor, and 50 amp electronic speed controller, have collectively enabled it to generate sufficient lift. This result is a clear demonstration that the Batbot, when positioned in the dynamic test bench, can exert enough force to lift and sustain its own weight, essentially achieving the primary objective of hovering.

The success of the Batbot in the dynamic test bench marks a significant milestone in this research project. It validates the effectiveness of the design upgrades implemented and underscores the potential of the Batbot as a viable model for exploring autonomous flight dynamics in robotics. Furthermore, the test bench's ability to provide a realistic and safe environment for assessing the Batbot's hovering capability proves to be an invaluable asset in the ongoing development and refinement of this project.

5 Outdoor Testing

After demonstrating the Batbot's ability to generate sufficient lift in a controlled environment, the next crucial step was to test it in real-world conditions.

5.1 Initial Outdoor Tests

The first of these outdoor tests involved suspending the Batbot from a long elastic attached to a tree. This test was pivotal for several reasons:

1. **Climbing Capability:** The Batbot demonstrated its capability to climb up the elastic, indicating effective lift generation in a less controlled environment.

2. **Stability Without Control Algorithms:** Remarkably, the Batbot exhibited good stability during these tests, even without the aid of controlling algorithms. This stability can be attributed to its physical design, suggesting a well-engineered balance and aerodynamic structure.

5.2 Hand-Controlled Hovering Tests

Subsequent tests involved manually controlling the Batbot's legs using a remote control (RC) controller, found in figure 19. The aim of these tests was threefold:

1. **Close Approximation of Hovering:** By manually controlling the Batbot, the goal was to approximate hovering as closely as possible. This approach was intended to glean valuable insights into the Batbot's hovering dynamics, which are crucial for further development.

2. **Rotation on 3 Axis:** Using basic leg positioning, we were able to generate rotation in the 3 Axis, providing insightful information that will be applied when developing the refined control algorithm.

3. **Basis for Algorithmic Refinement:**The insights gained from hand-controlled hovering are intended to serve as a foundation for refining the developed optimization algorithm. This refinement aims to enhance the Batbot's control strategy for more efficient and sustained hovering.

Figure 19: Outdoor test, with string

A crucial step was achieved when the Batbot was able to sustain hovering flight for the length of 2 seconds, seen in figure 20, proving this way that the physical capabilities of the Batbot are enough for sustained hovering and that all that is left to be done relies on the correct control of the hind legs.

Figure 20: 2 Second hovering achievement

6 Achievements and Future Plans

6.1 Achievements

This research has successfully accomplished several key objectives:

- Development of a system integrating the CMA algorithm with wireless communication and sensor data processing. This system has demonstrated its capability to optimize and learn effectively to achieve the set goals.
- Successful completion of the dynamic test bench, which has played a critical role in the testing process.
- Creation of a new Batbot model capable of lifting its own weight during hovering. This achievement is a significant milestone, as it demonstrates the practical applicability of our research in a real-world scenario. The use of the dynamic test bench has been instrumental in proving this capability.
- Achievement of a hovering flight duration of 2 seconds, marking a substantial advancement in the Batbot's performance.

6.2 Future Plans

Looking ahead, the project has outlined several key steps to further advance the Batbot's capabilities:

- Elongation of the hind legs to enhance their influence in generating rotational torque. This modification is expected to contribute significantly to the stability of the Batbot during hovering.
- Further refinement of the hind-leg movement using the optimization algorithm on the new version of the Batbot
- Integration of an accelerometer and gyroscope into the Batbot. This addition aims to enable self-sustained hovering by providing real-time feedback on the Batbot's orientation and acceleration, paving the way for more autonomous flight capabilities.

These future steps are designed to build upon the current successes and open new avenues for research and development in the field of autonomous robotic flight.

7 Conclusion

This research journey, exploring the intricate dynamics of the Batbot, has traversed various domains - from the conceptualization of a sophisticated robotic entity inspired by the natural mechanics of a bat, to the challenging realm of applying genetic algorithms for its autonomous control. Throughout this endeavor, the Batbot has evolved from a mere concept into a tangible representation of the potential held within the fusion of robotics, aerodynamics, and algorithmic control. The initial phase of this journey involved tackling the complexities of integrating diverse technologies and overcoming the practical challenges in robotic design and wireless communication. The successful transition to a more efficient microcontroller and sensor system laid a strong foundation for the subsequent phases of the project, enabling more accurate data collection and analysis. The heart of this research was the application of the Covariance Matrix Adaptation algorithm, a pioneering approach in the field of robotics. This process not only demonstrated the Batbot's ability to adapt and improve but also shed light on the limitations imposed by its physical design. The insights gained from the optimization process were crucial in guiding the redesign of the Batbot, emphasizing the need for a balanced approach that considers both algorithmic intelligence and mechanical efficiency. The dynamic test bench proved to be a milestone, offering a more realistic assessment of the Batbot's capabilities and revealing its potential to achieve stable hovering. The progression to outdoor testing further expanded our understanding of the Batbot's performance in real-world conditions, showcasing its ability to adapt and function outside controlled environments. The culmination of these experiments and developments brings us to a pivotal point where the future of autonomous robotic control seems more promising than ever. The Batbot project has illustrated that with innovative design, robust testing, and the intelligent application of genetic algorithms, the boundaries of what is possible in robotics continue to expand. The journey of the Batbot is not just a testament to technological advancement but also a beacon for future research in autonomous systems, where the synergy of different fields can lead to groundbreaking innovations. In conclusion, this research underscores the vast potential of evolutionary algorithms in training complex controlling strategies for autonomous systems. The Batbot's journey from concept to a near-autonomous entity highlights the importance of interdisciplinary collaboration and the continuous pursuit of improvement and adaptation. The learnings from this project will undoubtedly influence future endeavors in the realm of robotics and autonomous systems, paving the way for more efficient, intelligent, and adaptable machines. As we look ahead, the Batbot stands as a symbol of innovation and a stepping stone towards a future where autonomous robots seamlessly integrate into various aspects of life and work.