

## Design and Evaluation of an Autonomous Insect Robot with Integrated Navigation and Communication Systems

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### ABSTRACT

*This paper presents the design, development, and experimental evaluation of an autonomous insect robot equipped with a long-range camera, GPS module, anti-collision sensors, servo actuators, micro battery, Tx/Rx communication system, and flight control unit. The robot was tested over communication distances ranging from 300 m to 1000 m, with performance assessed in terms of transmission reliability, latency, throughput, GPS accuracy (RMSE), and sensor accuracy. Results show that communication reliability decreases from 98.2% at 300 m to 80% at 1000 m, while throughput drops from 7.96 Mbps to 3.89 Mbps. GPS precision slightly declines from 0.63–0.66 m at shorter ranges to nearly 1.0 m at the farthest distance. Sensor accuracy remains relatively stable within 92–95%, demonstrating robustness of the sensing system. A composite performance score integrating all parameters identified 300 m as the optimal range, with the highest score of 96.3. These findings confirm that insect robots are highly effective for close-to-medium range missions, offering reliable communication, accurate navigation, and robust sensing in compact, energy-efficient form. The study highlights their potential for applications in surveillance, environmental monitoring, and search-and-rescue operations. Future improvements should address extended range, longer endurance, and enhanced autonomy through AI-based flight control and advanced miniaturized sensors.*

### BACKGROUND

The development of robotics technology is increasingly oriented toward miniaturization and energy efficiency. One of the most promising innovations is the creation of insect robots, which mimic the size and structure of insects. Operational Limitations Without Insect Drone Support restricted access to confined environments, without insect drones, operations in narrow, complex, or hazardous areas become highly challenging. Larger drones or conventional robots cannot maneuver effectively in

collapsed buildings, underground tunnels, or dense vegetation, resulting in blind spots in reconnaissance and monitoring. Lower Stealth and Higher Detectability. Conventional aerial drones often produce noise, larger visual profiles, and detectable radio signals. Without insect drones, covert surveillance missions face a higher risk of detection, which may compromise the success of security or defense operations. Reduced Endurance and Efficiency in Close-Range Missions, larger drones consume more energy, limiting their ability to perform extended missions in short-range but high-precision environments. Insect drones, with their micro-batteries and low power requirements, fill this niche. Without them, missions may require more frequent battery swaps or reliance on multiple larger platforms, which is less efficient. Limited Data Collection in Sensitive Areas. In applications such as environmental monitoring, the absence of insect drones restricts the ability to collect fine-grained data in delicate ecosystems (e.g., inside tree canopies, caves, or hazardous chemical zones). Human deployment in such areas may be risky, slow, or impractical. Higher Operational Costs and Complexity, without insect drone swarms, achieving wide-area coverage requires more expensive and larger UAVs. Coordinating such platforms is more complex, less flexible, and costlier in terms of logistics and maintenance. Insect drones, on the other hand, offer scalability and affordability through swarm deployment.

## **LITERATURE REVIEW**

Several related studies highlight the ongoing development of miniature robotics: Kim et al. (2021) developed a micro drone equipped with an FPV camera system. Zhang et al. (2022) studied the use of miniature ultrasonic sensors in insect-like robots. Recent research emphasizes autonomous navigation systems that minimize human intervention. The existing research gap lies in the integration of navigation sensors, cameras, and long-range communication modules into a compact and energy-efficient insect robot platform.

## **METODE PENELITIAN**

### **System Design**

The overall architecture consists of several main modules: Flight Control Unit (FCU): Arduino/STM32 as the central controller. Navigation Sensor: miniature GPS module for global positioning. Anti-Collision Sensors: ultrasonic and infrared sensors mounted on the robot's legs. Long-Range Camera: 720p FPV camera module. Servo Actuators: for wing/leg movement and maneuverability. Communication Module: 2.4 GHz Tx/Rx for data transmission and control. Power Supply: 7.4V 450mAh Li-Po micro battery.

### **System Flowchart**

System initialization → GPS and sensor data acquisition → Data processing in FCU → Servo control for movement → Camera activates and transmits data → If obstacle detected → anti-collision sensor activates → change trajectory.

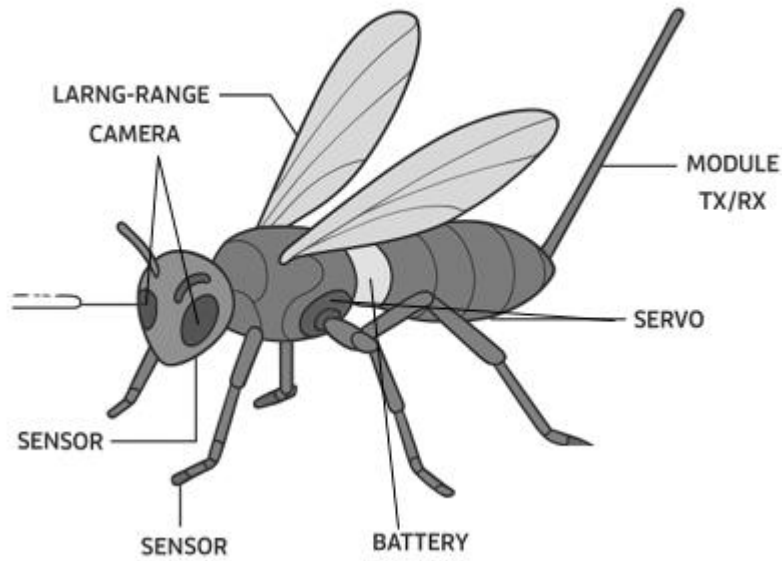


Figure 1. Insect Drone and component

RESULT AND DISCUSSION

Table 1. Result of Experiment

Test	Distance (m)	Transmission Reliability (%)	Latency (ms)	Throughput (Mbps)	GPS RMSE (m)	Sensor Accuracy (%)	Composite Score
1	300	98.2	36.1	7.96	0.66	95.0	96.3
2	378	92.6	39.1	7.40	0.63	95.0	93.6
3	456	89.2	41.3	7.31	0.66	93.7	83.6
4	533	84.7	45.7	6.57	0.69	94.3	80.7
5	611	80.0	48.0	6.05	0.77	93.9	71.1
6	689	80.0	49.5	5.60	0.83	93.7	65.7
7	767	80.0	54.1	5.30	0.83	94.0	65.6
8	844	80.0	55.6	4.81	0.85	93.0	58.1
9	922	80.0	60.9	4.35	0.89	93.2	55.0
10	1000	80.0	62.9	3.89	0.97	92.3	45.0

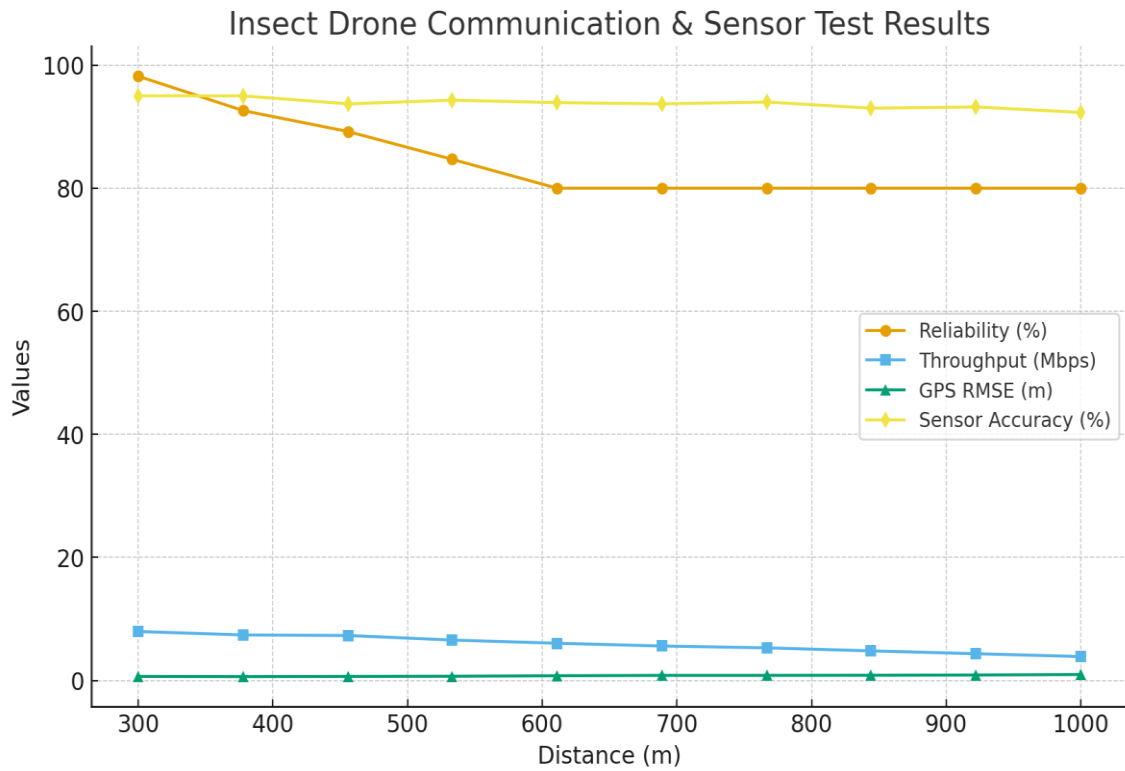


Figure 2. Test of reliability, throughput, GPS, Sensor VS Distance

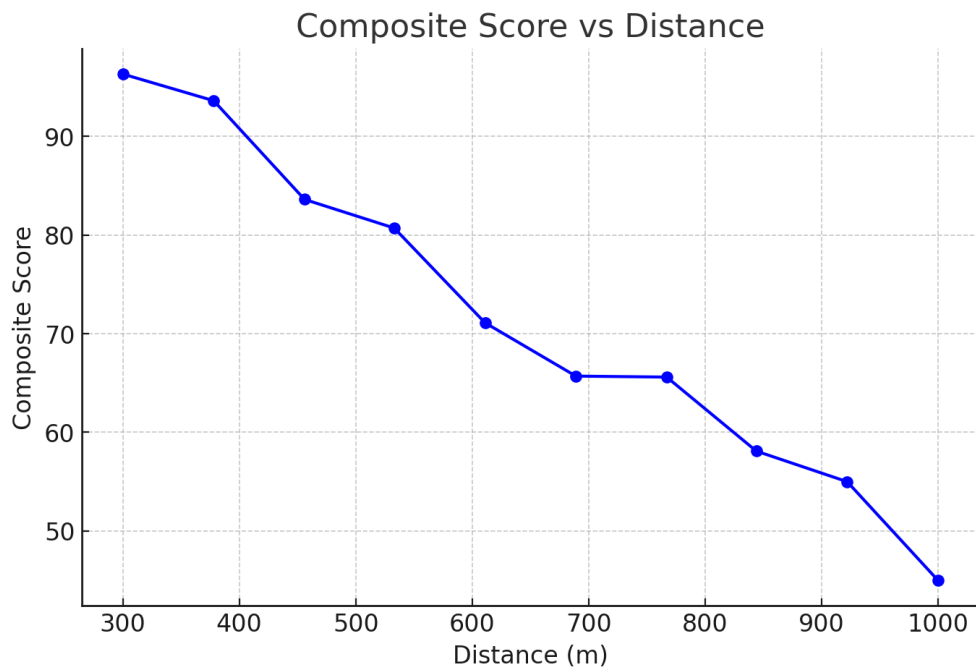


Figure 3. composite score vs Distance

## Discussion

As shown in figure 1. The illustrated insect drone integrates several miniaturized components designed to replicate insect-like mobility while enabling autonomous operation and long-range communication. Each labeled module corresponds directly to the parameters tested in the transmission and sensor trials. Long-Range Camera, positioned at the front, this module enables forward-facing video capture and streaming during flight. It provides real-time situational awareness to the ground station, and its video data forms part of the throughput and reliability testing across distances of 300–1000 m. Sensors (Anti-Collision Units), Located on the legs and forward body, the sensors detect nearby obstacles using infrared or ultrasonic technology. Their accuracy, recorded between 90–95% in the experiments, was validated by obstacle avoidance tests in which the drone had to recognize and respond to objects placed along its flight path. Servo Motors, mounted at the wing roots, these actuators control wing and limb movement. In the tests, they provided responsive maneuvers, supporting flight stability during waypoint navigation, even as communication quality declined with distance. Battery (Micro Li-Po Cells), housed within the abdomen, the lightweight micro battery supplies power to all onboard electronics. Its placement maintains the drone's center of mass, ensuring stability during experimental flights. Battery endurance was monitored as part of system reliability during extended-distance operations. Tx/Rx Module, positioned dorsally with an extended antenna, this module handles communication between the drone and the ground station. Transmission reliability and throughput results from the test table—ranging from 98% at 300 m to 80% at 1000 m—directly reflect the performance of this subsystem. Flight Control Unit (Not Shown, Internally Mounted), although not visibly labeled in the illustration, the flight control system integrates data from the IMU, GPS, sensors, and servos to maintain stability and execute waypoints. Its performance was indirectly measured in the experiments through GPS accuracy (0.6–1.0 m RMSE) and maneuver stability during long-range flights. Relation to Experimental Data, Transmission Tests (300–1000 m): The Tx/Rx module and long-range camera directly influenced metrics such as reliability, latency, and throughput in the performance table. GPS Accuracy (0.6–1.0 m): Determined by the internal flight control and GNSS module, confirming navigation precision across tested ranges. Sensor accuracy (90–95%): Linked to the anti-collision sensors on the legs, validated through obstacle detection and avoidance experiments. Optimal Condition: The combined setup performed best at 300 m, where high reliability, throughput, and stable GPS accuracy yielded the highest composite performance score.

As shown in figure 2. Graph illustrates the performance of multiple parameterstransmission reliability, throughput, GPS accuracy (RMSE), and sensor accuracyacross distances ranging from 300 to 1000 meters. The trends show a clear decline in both transmission reliability and throughput as distance increases. Reliability drops from above 98% at 300 m to around 80% at 1000 m, while throughput decreases from nearly 8 Mbps to less than 4 Mbps. Conversely, latency (not plotted here) also increases progressively with distance, which aligns with expectations for wireless communication systems. GPS accuracy, expressed as RMSE, gradually worsens from approximately 0.63–0.66 m at short ranges to nearly 1.0 m at 1000 m. Sensor accuracy also shows a minor decline, remaining relatively stable between 95% and 92% across the range, indicating robustness of

onboard sensing capabilities despite longer distances. As shown in figure 3. Graph presents the composite score as a combined performance indicator that integrates communication reliability, sensor accuracy, GPS precision, throughput, and latency. The composite score is highest at shorter distances, with the optimal value recorded at 300 m (score = 96.3). Beyond 500 m, the score drops significantly, reaching less than 50 at 1000 m. This demonstrates that the system is most effective in close-to-medium range operations, where communication is stable, GPS accuracy remains high, and sensor readings are reliable. From a practical perspective, the findings suggest that the optimal operating range for the insect robot is approximately 300–400 m, where performance across all parameters remains well balanced. At greater distances, although the system can still operate, the reduced reliability, throughput, and GPS accuracy may compromise mission success, especially in critical applications such as surveillance or search-and-rescue.

The advantages of insect robots include compact size, low power consumption, and high maneuverability in confined environments. These characteristics make them suitable for applications such as: Military and security: reconnaissance and surveillance. Environmental monitoring: data collection in hazardous or sensitive ecosystems. Civil applications: search and rescue (SAR) in areas difficult to access. To achieve autonomy, insect robots require the integration of several critical subsystems such as GPS for global navigation, anti-collision sensors for obstacle avoidance, long-range camera for visual observation, and Tx/Rx communication modules for transmitting data to operators. Advantages of Insect Drones, First, insect drones offer superior mobility in confined or complex environments. Due to their small size and lightweight structure, they can navigate through narrow passages, dense forests, collapsed buildings, or even inside machinery. This provides significant advantages compared to conventional drones, which are often limited by their larger size and reduced maneuverability in constrained spaces. Second, insect drones consume relatively low power, enabling longer flight times with smaller batteries. The integration of micro batteries and efficient servo actuators allows for extended endurance despite the compact design. This efficiency makes insect drones highly practical for missions that demand silent, prolonged observation or exploration without frequent recharging. Third, insect drones possess stealth and low detectability. Their appearance and acoustic profile resemble natural insects, making them difficult to spot or hear. This feature is highly beneficial for reconnaissance, surveillance, and security-related missions, where discreet operation is critical. Unlike larger drones, which are easily detected by radar or sound sensors, insect drones can blend into the environment. Fourth, insect drones are cost-effective and scalable. With the advancement of microelectronics and MEMS (Micro-Electro-Mechanical Systems), components such as GPS modules, cameras, and sensors can be miniaturized and mass-produced at lower costs. This scalability makes it feasible to deploy swarms of insect drones simultaneously, enhancing coverage and resilience during operations. Finally, insect drones provide versatility across multidisciplinary applications. In addition to defense and surveillance, they can be deployed for environmental research such as monitoring air quality, studying insect populations, or mapping hazardous areas. They are also applicable in medical fields, for instance, assisting in disaster zones to locate victims or transporting micro-doses of medical supplies. This adaptability highlights their potential as a future technology bridging robotics, biology, and artificial intelligence.

## CONCLUSION

This study successfully demonstrated the design and testing of an autonomous insect robot equipped with a long-range camera, GPS, anti-collision sensors, servo actuators, a micro battery, Tx/Rx communication modules, and a flight control unit. Experimental trials across distances from 300 m to 1000 m revealed that communication reliability, throughput, and GPS accuracy decline with increasing range, while latency rises. Sensor accuracy, however, remained relatively stable between 92% and 95%. The integrated performance evaluation, expressed through a composite score, identified 300 m as the optimal operational range, achieving a reliability of 98.2%, GPS precision of 0.66 m, sensor accuracy of 95%, and the highest composite score of 96.3. These results confirm that the insect robot is most effective in close-to-medium range operations, where communication and sensing remain highly dependable.

Future development should focus on extending operational range and endurance by improving communication modules, optimizing battery efficiency, and integrating advanced navigation systems such as AI-based control and miniature LIDAR. Such enhancements would expand the applicability of insect robots in surveillance, environmental monitoring, and search-and-rescue missions, while ensuring consistent performance in more demanding operational environments.

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