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Design of an IoT-Enabled Airflow-Adaptive Morphing Wing Prototype for UAV Systems

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Abstract

Morphing wings represent significant potential for enhancement of operational flexibility of UAVs with respect to varying flow conditions; however, the majority of existing solutions are based on relatively sophisticated systems and require special instrumentation and/or computation-intensive control algorithms. This research describes an Internet-of-Things-based morphing wing prototype conducting low-cost experiments related to adaptive behavior of morphing systems based on air-flow-dependent geometrical adjustments. The prototype includes two sensing channels of air flow, an Arduino UNO microcontroller, a decision-making mechanism based on threshold criteria implemented by the microcontroller, mechanical actuation controlled by a servo, visual feedback via an LCD display, a manual controlling mode, as well as wireless monitoring. Experiments were carried out at air flow velocities of 1.0 to 5.0 m/s, during which variations of the sensing output, servo command, response time and repeatability were investigated. It was found that both sensing channels produced an increasing output in the investigated range of velocities, while servo commands varied from 15° to 75°. Response times were within 318-420 ms and 96% of 50-trial experiment were successful.

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1. Introduction

The issue of aerodynamic efficiency is one of the basic parameters considered during the designing process of aircraft and UAVs, as it affects such factors as flight duration, fuel consumption, handling performance, and stability. Fixed-wing aircraft are usually designed to perform their operations adequately at specific conditions only. Changes in such factors as velocity, pressure, turbulence, and mission needs can move an aircraft away from the optimal aerodynamic configuration. Thus, the use of fixed wing configuration does not allow achieving the optimum performance of an aircraft within the whole envelope. It gave rise to such innovations as morphing wings.

The concept of morphing wings is, to some extent, motivated by biological fliers like birds, who continually change the shape of their wings while taking off, cruising, navigating, and landing. For artificial systems, such capability can be obtained by using flexible structures, mechanical joints, smart materials, in-built controllers, and active actuators. It has been shown through prior work that the manipulation of geometry helps in achieving aerodynamic optimization, drag minimization, stability, and mission adaptability. However, most morphing-wing systems currently available involve complicated structural mechanisms, control systems, costly sensors, or special wind tunnel setups.

The study proposes a morphing wing prototype that is designed using two channels for sensing airflow, an Arduino UNO controller, a servo-driven mechanism, an LCD, switches, and Wi-Fi monitoring. In this case, the controller captures air flow sensors' signals, determines the condition from the captured data by applying decision-making algorithms, and issues a command to the servo mechanism in order to alter the physical setup of the prototype. The use of two sensors allows obtaining information from two different spots where the air flow is being monitored.

The primary objective is to demonstrate a simple, cost-effective platform for real-time airflow-responsive morphing using readily available embedded hardware. Experimental evaluation focuses on verifying changes in sensor response under varying airflow conditions, corresponding actuator movement, and integrated monitoring functionality.

2. Literature Review

The initial study on morphing wing demonstrated optimization of the wing in real time through wind tunnel experiments and confirmed that wing geometry can be modified and analyzed with changing aerodynamic conditions [1]. A later study on the morphing laminar wing demonstrated the aerostructure model for morphing wing optimization and focused on the combined effect of structure and aerodynamics [2].

In addition, a combination of computer simulations and experiments was used to prove the concept of active morphing wings [3]. These studies showed the significance of the correlation between computational predictions and physical prototype performance, especially in terms of deformation properties and aerodynamics. Studies related to actuating a smart shape of an airfoil proved that the performance of morphing wings depended on both structural deformability and an effective control method to transform required shapes into actuator movements [4]. A study on wind-tunnel tests of a controlled rotary actuator was another example of the importance of precise mechanical actuation [5].

Moreover, the studies have included research toward meeting some aerodynamic requirements by adapting the geometry intentionally. An experiment with a morphing wing-tip model, which was designed for drag minimization at low-speeds and evaluated with the help of infrared transition measurement in a wind tunnel environment, is an example of research [6]. With this study, it was demonstrated that geometric modifications can be made depending on the aerodynamic regime. In another study, an integration of aerodynamic analysis with the dynamic modeling and control of a morphing aircraft was performed, thus proving that not only aerodynamic properties, but also the dynamics and stability of the aircraft are affected by wing geometry [7].

Recent studies have focused more on control systems and adaptive systems. A survey of morphing aircraft control techniques found sensing, feedback, decision making, and actuation to be essential parts of any adaptive system [8]. Moreover, the surveyed techniques show that the choice of a particular controller is dependent on the dynamics of actuators, complexity of the system, computing resources, and mission requirements. In a separate but simultaneous process, adaptation of morphing wings and tail has been achieved by bird-like drones for flight stability, resilience, and efficiency [9].

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More possibilities for morphing-wing creation can be found through computational intelligence. Deep learning technique used for fast aerodynamic assessment of morphing wing structures proved that data-driven approaches could be employed to simplify computation needed in the evaluation process [10]. Even though the approach above could serve in future applications of real-time optimization, it usually needs more computational power and proper datasets than traditional embedded controller systems. The concept of morphing has even been applied to hybrid drones with a rover which is capable of conducting rescue operations in difficult conditions [11].

Overall, the literature highlights significant advancement made in real-time optimization, aerostructure analysis, experimentation, intelligent actuation, drag reduction morphing, control of flight vehicles, adaptive UAVs, and intelligent aerodynamic prediction [1]-[11]. However, most of the methods involve complex mechanical design, sophisticated wind tunnel test beds, aerodynamic simulations, and complicated algorithms. There has not been sufficient emphasis on simplistic and cost-effective design approaches involving integration of multi-channel airflow sensing, processing, actuation, visualizations, and wireless measurement systems. This work aims to fill up this gap through development of Arduino-based morphing technology prototype.

3. Proposed Methodology

The proposed methodology involves using a two-channel flow-sensing control scheme that translates measured flow variations into actuator commands through adaptive configuration reconfiguration. As an alternative to computationally demanding aerodynamic optimization, the technique involves employing real-time sensor data acquisition and lightweight embedded classification for low-cost UAV application prototyping.

The general process involved in implementing the methodology consists of four major steps, namely two-channel flow sensing, sensor data processing and differentials computation, operation state classification and actuator command generation using a threshold, and local and wireless status monitoring. The functional framework utilized in performing the steps is depicted in Figure 1, whereas Table 1 presents the hardware and software components used in the process.

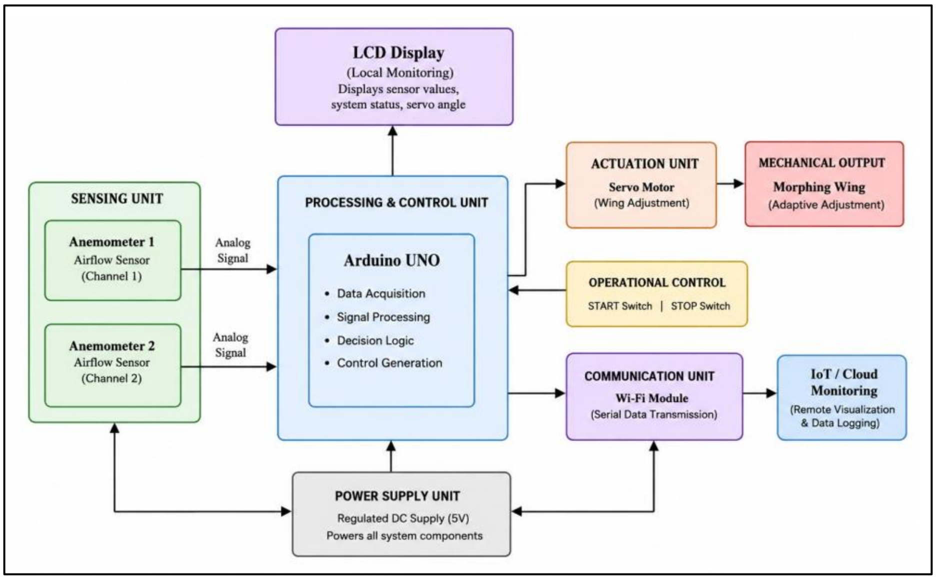

Figure 1. Block diagram of the IoT enabled airflow-adaptive morphing wing system

Figure 1 shows that Anemometer 1 and Anemometer 2 provide air flow sensing inputs to the Arduino UNO, where there is sensing and embedded decision making. As per the operating condition sensed by the system, the controller provides a command to the servo motor to adjust the mechanical system. There is an LCD display for local readings, while the START and STOP buttons control the working of the prototype.

Table 1. Hardware and software resources used in the proposed system

Hardware/Software	Purpose
Arduino UNO	Sensor acquisition and control processing
Two Anemometer Channels	Dual-location airflow sensing
Signal-Conditioning Circuit	Sensor-signal conditioning
Servo Motor	Adaptive mechanical actuation
Liquid Crystal Display (LCD)	Local status display
Wi-Fi Communication Module	Wireless status transmission
START and STOP Switches	Manual operational control
Regulated Power Supply	Stable circuit power
Mobile Monitoring Interface	Remote status observation
Arduino IDE	Embedded program development
Embedded C	Controller program implementation
Threshold-Based Control Logic	Airflow-state evaluation and servo selection

Two anemometer channels will be employed for the detection of airflow fluctuations using different sensing points. The readings from the sensors are transmitted via the respective interface and conditioning circuit to the Arduino UNO. The electrical connections involving the sensing channels, controller, LCD display, WiFi module, switches, servo motor, and power are shown in Figure 2.

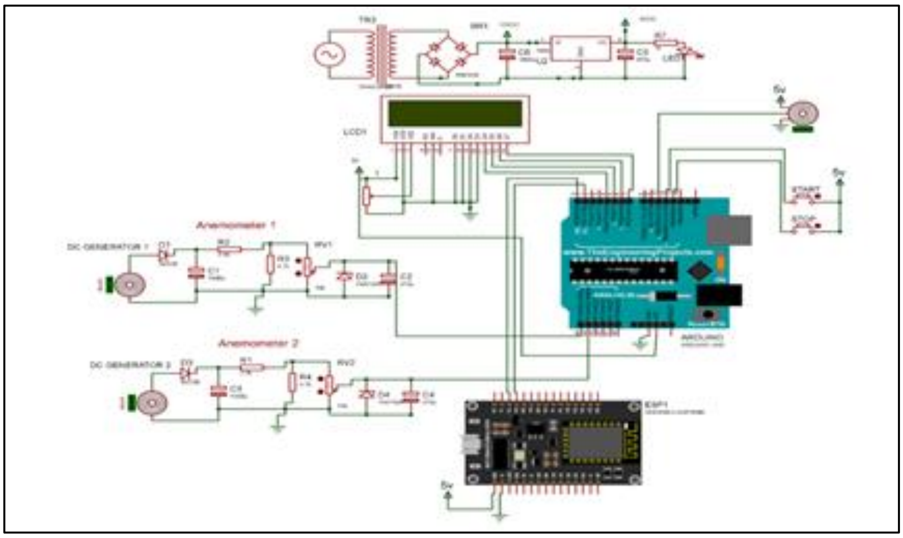

Figure 2. Circuit schematic of the proposed system

For the two sensing channels, the digitized measurements can be represented as

$$S_1 = ADC(V_{A1})$$

and

$$S_2 = ADC(V_{A2})$$

where V_{A1} and V_{A2} are the conditioned sensor voltages, and S_1 and S_2 are the corresponding digital values acquired by the microcontroller. A differential parameter may be defined as

$$\Delta S = |S_1 - S_2|$$

where ΔS indicates the relative difference between the two airflow measurements. The controller uses the acquired sensor states to identify changes in the operating airflow condition.

The Arduino UNO acts as the central control unit. After initialization, it periodically samples the sensor channels and evaluates the measured values using predefined control thresholds. A general threshold-based control rule is expressed as

$$\theta_c = \begin{cases} \theta_1, & S < T_1 \\ \theta_2, & T_1 \le S < T_2 \\ \theta_3, & S \ge T_2 \end{cases}$$

where S denotes the processed airflow-related input, T_1 and T_2 are experimentally selected thresholds, and θ_1, θ_2, and θ_3 are predefined actuator positions.

For dual-channel operation, the control decision can be generalized as

$$\theta_s = f(S_1, S_2, \Delta S)$$

where θ_s is the commanded servo position and $f(\cdot)$ represents the embedded decision logic. This lightweight strategy was selected because it can be executed directly on the Arduino UNO without requiring high-performance computing hardware.

After detecting the air flow state, the microcontroller sends a corresponding signal to the servo motor, which translates this electrical signal into a physical movement of the morphing surface mounted on it.

The complete prototype operation follows the control sequence defined in Algorithm 1

Algorithm 1: Embedded airflow-responsive control sequence

Input: Conditioned airflow signals VA1 and VA2
Output: Servo command θs and monitoring status

```
1:  Initialize controller, sensor inputs, servo, LCD, and Wi-Fi module
2:  Set the system to the initial operating state
3:  while system is active do
4:      Read START and STOP switch states
5:      if START is active and STOP is inactive then
6:          Acquire VA1 and VA2
7:          Convert sensor signals to digital values:
              S1 ← ADC(VA1)
              S2 ← ADC(VA2)
8:          Compute inter-channel difference:
              ΔS ← |S1 − S2|
9:          Evaluate the processed airflow-related input S
10:         if S < T1 then
11:             θs ← θ1
12:         else if T1 ≤ S < T2 then
13:             θs ← θ2
14:         else
15:             θs ← θ3
16:         end if
17:         Apply θs to the servo motor
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```
        Update LCD status
        Transmit system status through Wi-Fi
    end if
end while
Stop system operation
```

4. Results and Discussion

The prototype was tested through varied air flow conditions to determine the functional flexibility, wireless communication capabilities, sensor response properties, actuator response, and dynamic response. The experimental results presented in the present manuscript indicate that there was variation in the sensor response and actuator response due to variation in air flow. The developed hardware prototype is shown in Figure 3. The prototype comprises the control board, LCD display, wireless communication board, sensor circuitry, electrical connections, and air flow generation setup.

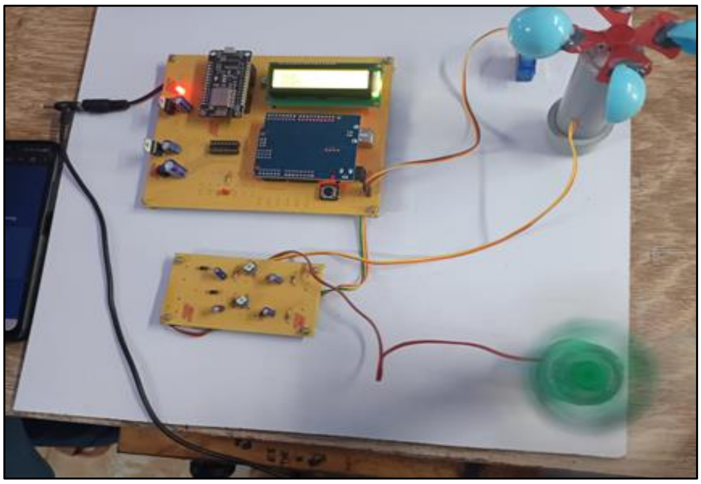

Figure 3. Experimental prototype of the airflow-based adaptive control system

During testing, airflow conditions were varied using the available laboratory arrangement. The two sensor inputs recorded the changes in flow conditions. This information is then processed by the Arduino UNO that sends a signal to the actuator in accordance with the programed decision logic.

Figure 4. IoT-based mobile monitoring interface during prototype operation

Wireless monitoring configuration was tested during prototype testing through the use of an Internet of Things-based mobile interface coupled with the communication capability of Wi-Fi module, illustrated in Figure 4. The mobile interface allowed remote monitoring of the operational status of the system while sensing, decision-making, and servo activation tasks were performed locally on the embedded control system. Successful operation of the mobile interface along with the prototype verified the wireless capability of the prototype.

Five airflow conditions ranging between 1.0 m/s and 5.0 m/s were selected for initial quantitative tests. Table 2 presents sensor outputs, inter-sensor difference, and servo activation angle.

Table 2. Preliminary quantitative response under different airflow conditions

Airflow velocity (m/s)	Sensor 1 (ADC)	Sensor 2 (ADC)	(\Delta S) (ADC)	Servo angle (°)	Response time (ms)
1	218	205	13	15	420
2	326	309	17	30	395
3	438	416	22	45	368
4	557	529	28	60	342
5	681	646	35	75	318

The results indicate systematic variation in all evaluated parameters. Higher airflow resulted in increased values of sensor outputs and actuator controls while the initial reaction time tended to decrease. These dependencies are discussed in the following sub-sections. The variations in both sensor outputs versus airflow velocity are shown in Figure 5.

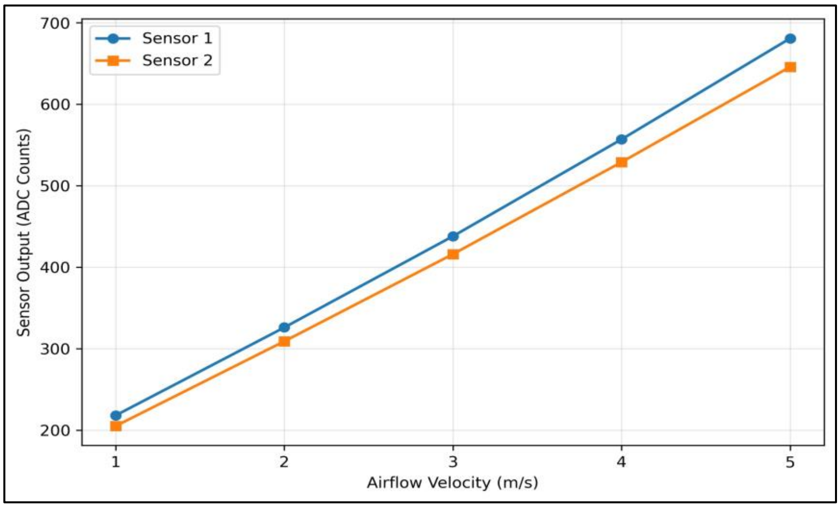

Figure 5. Variation of airflow sensor outputs with airflow velocity

As depicted in Figure 5, there was an increment in the value of Sensor 1 from 218 ADC units to 681 ADC units from 1.0 m/s to 5.0 m/s, which is a 212.4% increase. Also, there was an increment in the value of Sensor 2 from 205 to 646 ADC units, which corresponds to an increase of 215.1%. The similarity of the two trends shows the similarities in their sensitivity to increased airflow speed. However, there was an increase in the difference between the two channels from 13 to 35 ADC units.

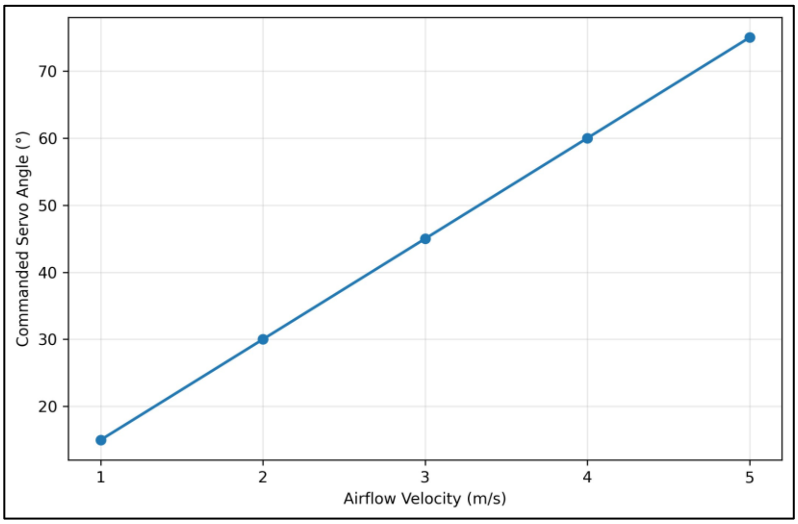

Figure 6. Variation of commanded servo angle with airflow velocity

The relationship between airflow velocity and commanded servo angle is shown in Figure 6. As the commanded angle changed from 15° at 1.0 m/s to 75° at 5.0 m/s, a total angular variation of 60° was observed. This steady increase signifies that there is a monotonic connection between the assessed air flow condition and the actuator command.

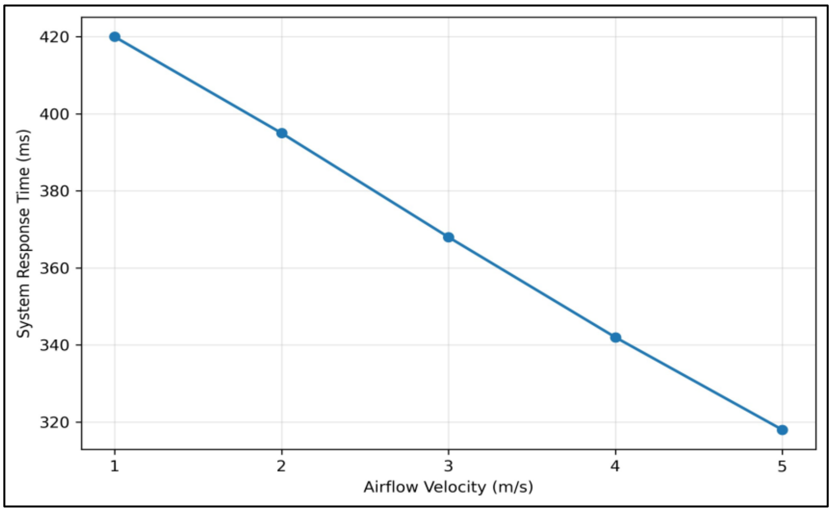

Figure 7. Variation of system response time with airflow velocity

The response-time variation is presented in Figure 7. Response time was reduced from 420 ms when speed was 1.0 m/s to 318 ms when speed was 5.0 m/s, which represents a total reduction of about 24.3%. The mean response time for the five trials was 368.6 ms, with the median at 368 ms and a range of 102 ms.

Table 3. Preliminary repeatability assessment

Airflow velocity (m/s)	Trials	Correct responses	Success rate (%)
1	10	9	90
2	10	10	100
3	10	10	100
4	10	9	90
5	10	10	100
Overall	50	48	96

A preliminary repeatability assessment results are presented in Table 3. It produced 48 correct responses from 50 trials, corresponding to an overall success rate of 96%. The lower ratios for 1.0 m/s and 4.0 m/s could imply possible sensitivity to close-to-threshold values, temporary changes in airflow, sensor noise, or even actuator delay. In subsequent testing, any trial must be supplemented with standard deviation and confidence interval calculations to ensure statistical validity.

5. Conclusion

The experiment shows that air-flow responsive structural adaptation is possible through an architecture composed of easily available embedded hardware, without using any complex aerodynamics optimization systems. One of the important features of the architecture used in the experiment is the possibility to implement a compact dual channel system, where spatially distinct flow measurements are mapped to certain mechanical configurations while retaining the access to the operational information locally and through wireless connections. The monotonic actuation proves the ability of the implemented control system to distinguish varying input parameters and configure the architecture appropriately. In addition, fast operation time and high preliminary repeatability demonstrate the appropriateness of the architecture for conducting laboratory-level tests of the adaptive systems. However, the current research does not measure the improvements of aerodynamics performance, since the commanded position of the servos cannot provide information about the wing deflection or increase in the lift and decrease of the drag. Calibration of the sensors, compliance of the links, threshold sensitivity, and air-flow changes should be tested further. Therefore, further development of the system should focus on closed-loop control, independent geometry measurements, uncertainty analysis, statistical testing, and wind tunnel tests.

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