Efficient Fan Design Using Propellers for Fan Array Wind Tunnels

Natania Middleton[1], Emma Grace Lumm[2], Jaretzy Nicolas[3], Cherno M. Keita[4], Daniel Foti[5]

Department of Mechanical Engineering, University of Memphis, Memphis, Tennessee, 38152 United States of America

The operation of unmanned aerial vehicles (UAVs) in adverse environments requires the ability for repeatable testing of complex, turbulent conditions. Traditional methods such as field studies and wind tunnels often lack the controllability and spatial flexibility required to simulate realistic, time-varying wind profiles, respectively. An alternative testing facility is a modular, open-concept fan array wind tunnel that utilizes independent fan "pixels" to arbitrary wind conditions. However, current fan pixels are standard computer server fans, which consume significant energy in off-design conditions. We investigate the replacement of these units with UAV motors and UAV-like propellers to improve the thrust-to-electric power ratio. This includes the overall increase in the diameter of the fan. We explore the design parameters space of a number of blades, pitch, twist, and sectional chord length and shape by employing blade element momentum (BEM) theory. Based on aerodynamic principles, it is expected that optimizing the blade geometry will significantly reduce energy consumption while maintaining the high thrust levels required for simulated flight conditions. Ultimately, this design study will lead to a printable fan design that will be used experimentally tested in the laboratory.

I. Introduction

The rapid proliferation of unmanned aerial vehicles (UAVs) has revolutionized sectors ranging from precision agriculture and urban package delivery to advanced operations in challenging environments. However, ensuring the flight stability of these systems within the turbulent atmospheric boundary layer remains a significant engineering challenge. For autonomous systems operating in high-stakes scenarios, the ability to navigate sudden gust or complex\wind profiles is not just a matter of efficiency, but of operational survival.

Traditional wind tunnel facilities, while excellent for high-speed aerodynamic characterization of conventional aircraft, are not well-suited for the low-speed, highly turbulent, and non-uniform flow fields that UAVs encounter in "real-world" environments. Enclosed test sections limit the maneuverability of the aircraft and often fail to replicate the large-scale turbulent eddies present in stormy conditions or the unpredictable wakes found in tactically challenging zones. To bridge this gap, fan array wind tunnels (FAWTs), or "meso-scale" facilities, have been developed [1-6]. These facilities consist of a large grid of individually controlled fan "pixels." By modulating the RPM of each pixel, researchers can programmatically generate arbitrary wind profiles and complex gust scenarios, allowing for the repeatable testing of flight controllers against the very disturbances that cause system failure in the field.

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[1]Undergraduate Sophomore, Department of Mechanical Engineering, Student Member Natania Middleton (1810643)
[2]Undergraduate Sophomore, Department of Mechanical Engineering, Student Member Jaretzy Nicolas (1823361)
[3]Undergraduate Sophomore, Department of Mechanical Engineering, Student Member Cherno M. Keita (1925329)
[4]Undergraduate Sophomore, Department of Mechanical Engineering, Student Member Emma G. Lumm (1923943)
[5]Assoicate Professor, Department of Mechanical Engineering, AIAA Member (450024)

The FAWT facility at the University of Memphis[1,3] currently utilizes modular units composed of Delta Electronics GFM0812DS fans. These are 80 mm, dual-stage, counter-rotating coaxial units originally designed for high-density server rack cooling. While these fans can reach exit velocities near 16 m/s, they present several aerodynamic drawbacks when applied to wind tunnel jet generation. Server fans are engineered to overcome high static pressure within enclosed electronics, prioritizing pressure over the thrust-to-power efficiency required for open-jet environments. This leads to excessive power consumption when scaling to large arrays, which can limit the duration and intensity of long-endurance testing cycles.

Furthermore, recent research indicates that the interaction between these small, high-speed jets leads to a non-classical development of the test section. The jets merge and form a unified flow field that is highly sensitive to the surrounding laboratory geometry, creating recirculation zones that can bias experimental data. For missions requiring a high-fidelity replication of atmospheric disturbances, the residual swirl and high-frequency turbulence produced by these cooling fans are not optimal.

The objective of this research is to move away from "off-the-shelf" cooling fans and towards an UAV-like propeller optimized specifically for the FAWT's operational envelope. By utilizing motors and propellers designed for propulsion rather than cooling, we aim to increase the aerodynamic efficiency of each pixel [2]. This requires a redesign framework to determine the optimal blade geometry, including the number of blades, pitch angles, and chord distributions.

By optimizing these "pixels," we can create a more energy-efficient facility capable of generating the high-velocity, low-turbulence jets necessary for testing the next generation of autonomous systems. The ability to validate flight stability in a controlled, "pixelated" wind environment is a critical step toward reliable autonomous operation in the world's most challenging environments.

II. Numerical Methods

A. Blade Element Momentum Model

The aerodynamic performance of the fan is predicted using a steady blade element momentum (BEM) formulation [7], which combines one-dimensional momentum theory with two-dimensional sectional aerodynamics. The method provides an efficient reduced-order model for rotating lifting surfaces under the assumptions of incompressible flow, axisymmetric, and negligible radial transport. This approach allows for rapid iteration across the design parameter space of blade pitch, twist, and chord distribution.

B. Inflow Kinematics

The local inflow angle ϕ and angle of attack α are determined by the axial and tangential induction factors, a and $a^{'}$:

$$\phi = \tan^{-1}\left(\frac{U_\infty(1-a)}{\Omega r(1+a')}\right) \tag{1}$$

$$\alpha = \theta(r) - \phi \tag{2}$$

C. Sectional Forces

The local forces on each blade element are computed using lift (C_{L}) and drag (C_{D}) coefficients:

$$dF_{\mathrm{x}} = dL\cos\phi - dD\sin\phi \tag{3}$$

$$dF_{0} = dL\sin\phi + \cos\phi \tag{4}$$

D. Momentum Balance

The induction factors are found by equating the blade forces to the change in air momentum:

$$B \cdot dF_x = 4\pi\rho U_\infty^2 a(1-a) r\, dr \quad (5)$$

$$Br \cdot dF_\theta = 4\pi\rho U_\infty \Omega a'(1-a) r^3\, dr \quad (6)$$

E. Performance Integration

Total thrust *T* and *P* are obtained by integrating the elemental forces along the blade span *R*:

$$T = \int_0^R dT \quad (7)$$

$$P = \Omega \int_0^R dQ \quad (8)$$

III. Results and Discussion

The performance of the fan array pixels was evaluated across a range of geometric parameters while maintaining a constant rotation rate (**Ω**), module radius, and hub radius. The following analysis explores the sensitivity of thrust, velocity, and power coefficients to the number of blades, pitch angles, and chord distributions

A. Thrust and Velocity Sensitivity to Blade Count and Pitch

Initial BEM analysis focused on the relationship between thrust and the number of blades at three distinct pitch angles (2°, 6°, and 10°). As observed in the three-panel plot results (Figure 1), increasing both the pitch angle and the chord length directly maximizing the total thrust. However, a diminishing return was observed as the blade count increased; the thrust values began to taper off, showing less dramatic gains beyond a certain threshold. Similarly, the relationship between thrust and pitch angle demonstrated a direct correlation with chord length. Configurations with longer chord lengths exhibited a steeper overall slope, indicating a higher sensitivity to pitch adjustments (Figure 2).

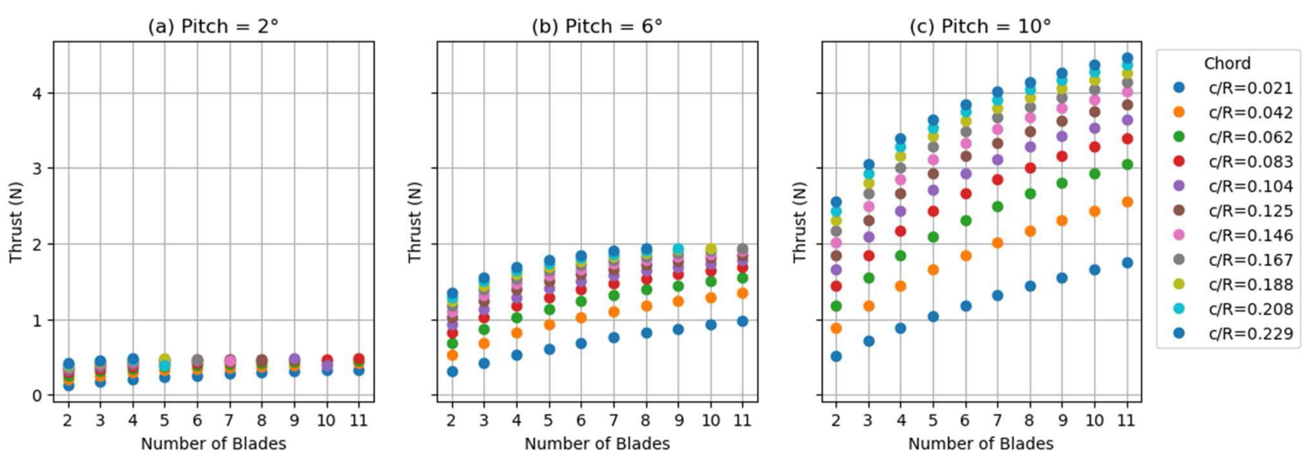

Figure 1: Thrust vs. Number of Blades for 2°, 6°, and 10° Pitch Angles

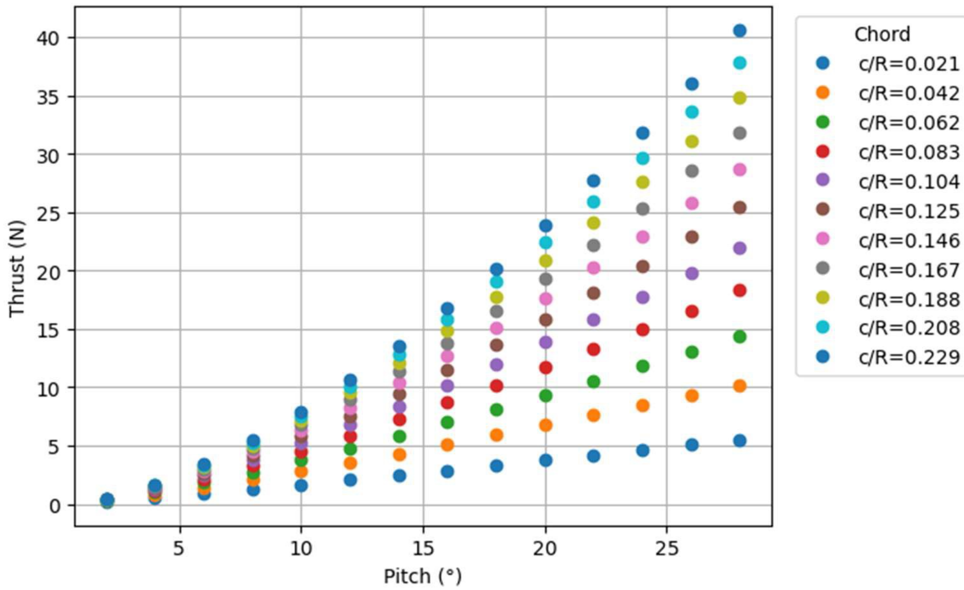

Figure 2: Thrust vs. Pitch Angle for Varying Chord-to-Radius Ratios.

B. Velocity Trends and Performance Drop-offs

The velocity output mirrored numerous trends seen in the thrust data, particularly regarding the influence of pitch and chord length (Figure 3). However, the relationship between velocity and the number of blades revealed critical performance limits. For the 2° pitch case, velocity gains began to stagnate for most chord ratios after 5 blades, with the c/R = 0.021 configuration showing a noticeable drop-off in performance at higher blade counts. In contrast, the 6°pitch configuration demonstrated the capacity to support a larger quantity of blades, maintaining performance until a similar plateau or slight drop-off occurred around 9 to 10 blades (Figure 4). A pitch angle of 10° produced the most thrust-efficient results, with the plateau not visible on the range of blades depicted.

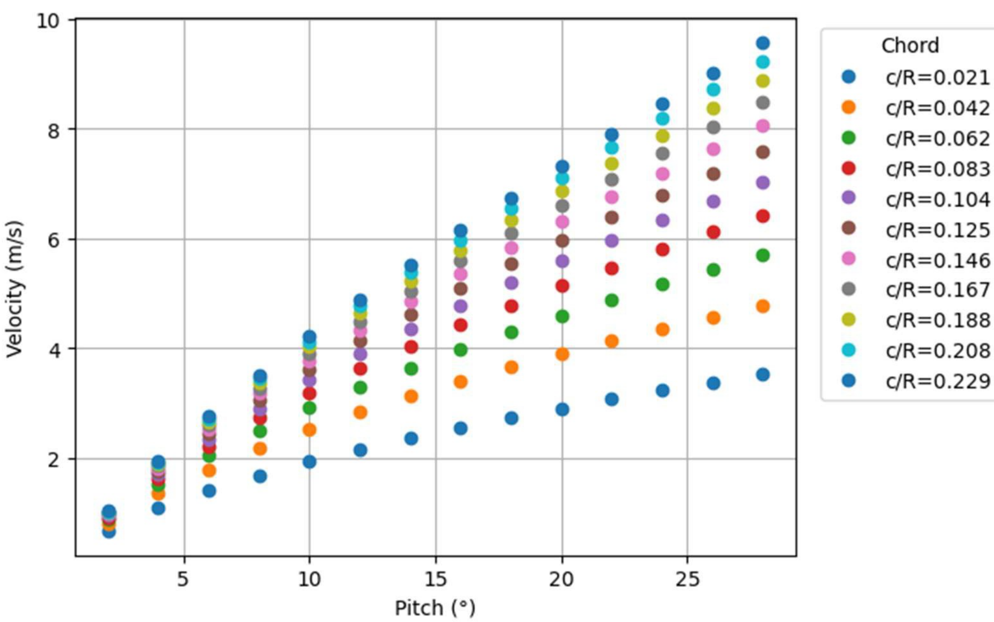

Figure 3: Velocity Output vs. Pitch Angle

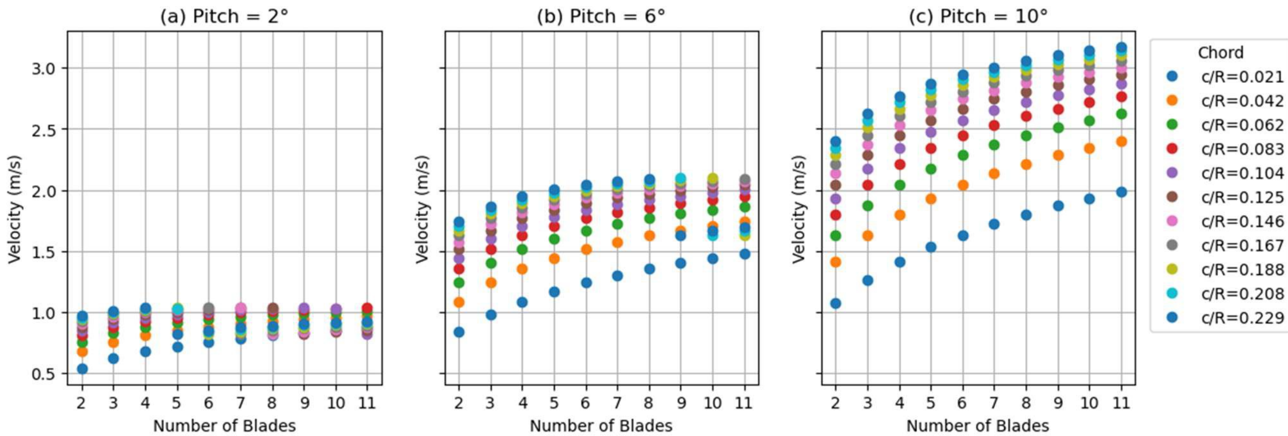

Figure 4: Velocity vs. Number of Blades for 2°, 6°, and 10° Pitch Angles

C. Coefficient Analysis and Solidity

The relationship between the thrust coefficient (C_t) and solidity (σ) further highlights the impact of pitch angle. The 6° pitch configuration consistently produced higher coefficients than the 2° pitch across all tested solidity values. Interestingly, the 2° pitch configuration appeared to reach a maximum thrust coefficient at a solidity of approximately 0.32, after which the performance plateaued or slightly declined, while the higher 6° pitch continued to show increases in C_p solidity increased. Consistent with the previous findings, a pitch angle of 10° produced the most effective results with respect to the thrust coefficient, with c/R = 0.062 surpassing the other chord ratios.

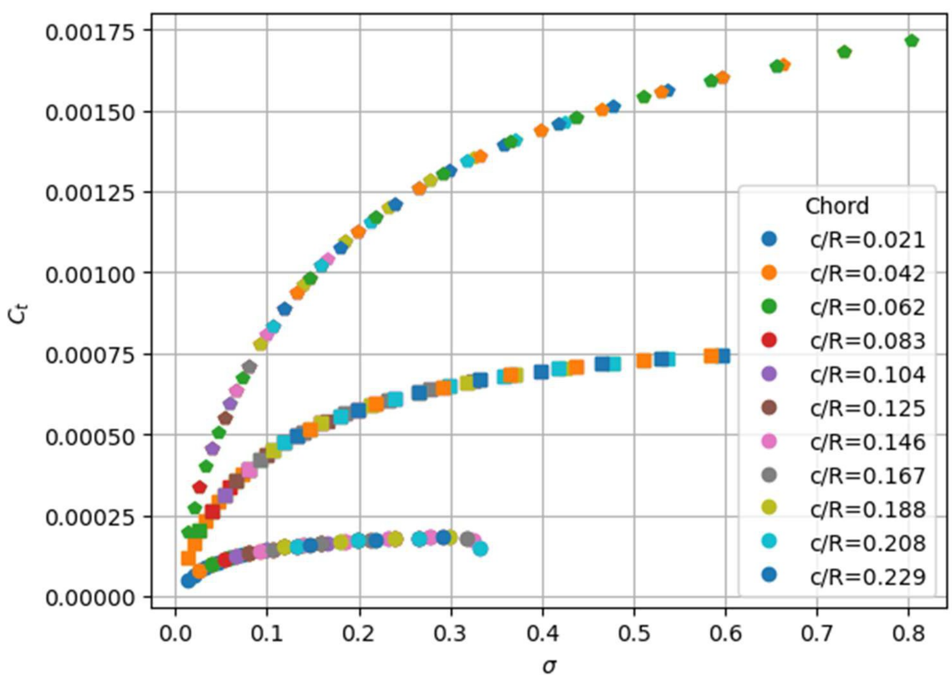

Figure 5: Thrust Coefficient vs. Solidity for 2°, 6°, and 10° Pitch Angles

Finally, the coefficients of power (C_p) versus pitch and blade count were evaluated. While both parameters showed a direct relationship with power requirements initially, the data indicates that as the blade count increases toward 9 and beyond, the rate of increase in power consumption begins to level off for several chord ratios. This suggests an upper limit for effective aerodynamic loading within this specific module geometry, where adding more blades results in diminishing gains in performance relative to the power consumed.

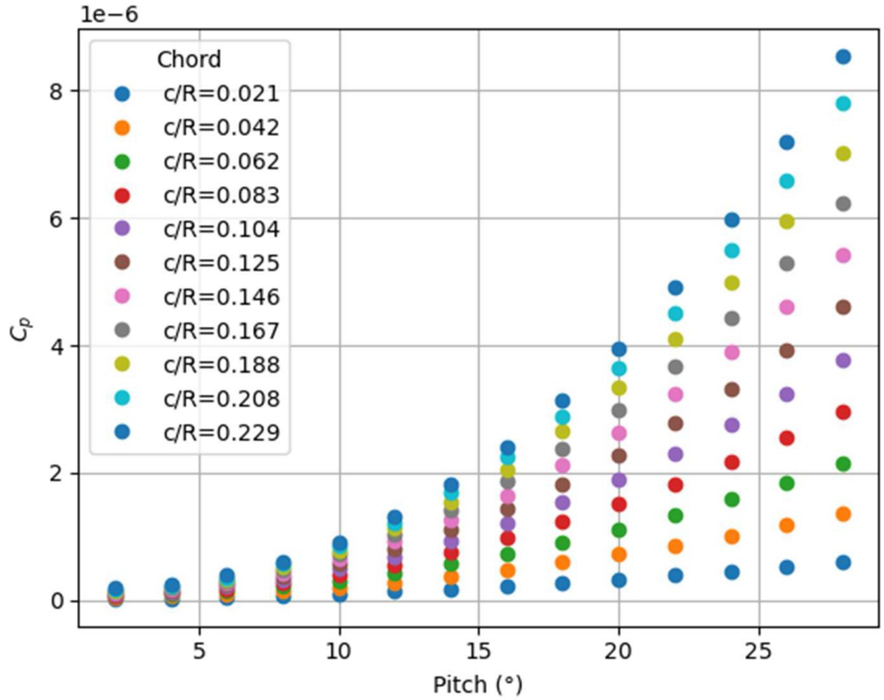

Figure 6: Power Coefficient vs. Pitch Angle

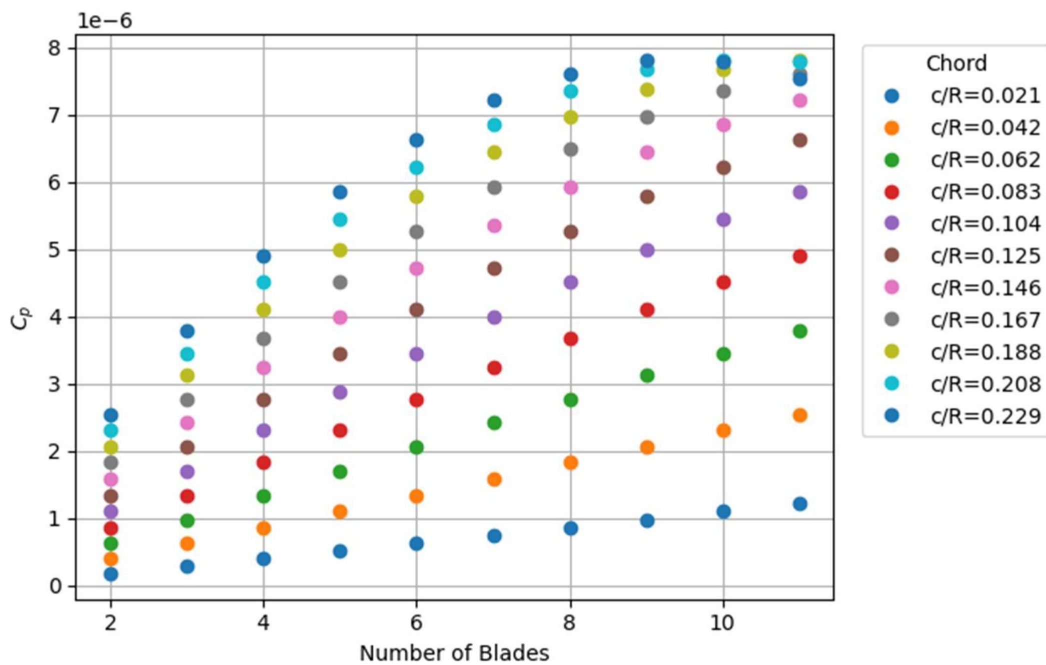

Figure 7: Power Coefficient vs. Number of Blades for Various Chord Ratios

IV. **Conclusion**

The objective of this research was to transition from "off-the-shelf" computer server cooling fans to UAV-like propellers specifically optimized for the operational envelope of the Fan Array Wind Tunnel (FAWT) facility at the University of Memphis. By employing a steady Blade Element Momentum (BEM) formulation, this study explored the design parameter space of number of blades, pitch and chord distribution to improve thrust-to-electric power ratios. The results indicate that a pitch angle of 10° consistently produced the most effective results regarding the thrust coefficient, with the chord-to-radius ratio of $c/R = 0.062$ surpassing other tested configurations. While increasing pitch and chord length generally maximized total thrust, the data revealed critical performance limits and diminishing returns as blade counts increased. Specifically, velocity gains for the 2° pitch configuration stagnated after 5 blades, while the 6° configuration maintained performance until a plateau occurred around 9 to 10 blades. Without a plateau present on the graph, velocity gains for the 10° pitch surpassed both the 2° and the 6° pitch configuration.

Furthermore, the analysis of power coefficients (C_p) suggests an upper limit for effective aerodynamic loading within this specific module geometry, as the rate of increase in power consumption begins to level off at higher blade counts. These findings provide a necessary framework for reducing energy consumption while maintaining the high thrust levels required to simulate realistic, time-varying wind profiles for UAV testing

Building upon these numerical findings, the next phase of this research will focus on the development of a 3D-printable fan design based on the optimized geometric parameters. These units will be experimentally tested in the laboratory to validate the BEM predictions against physical performance data. Additionally, future studies will evaluate how these optimized "pixels" interact within a full array to ensure the generation of high-velocity, low-turbulence jets necessary for testing the next generation of autonomous systems.

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VI. **References**

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