

Flight-Log-Based Assessment and Center-of-Gravity-Oriented Redesign of a Large Flying-Wing VTOL UAV

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Abstract: *This study evaluates the VTOL behaviour of a 4.18 m-span, 15.5 kg flying-wing UAV and proposes a simplified propulsion-layout redesign. Three flights of the original tri-rotor configuration were analysed using attitude, motor and servo PWM, altitude, and vibration data. Roll and pitch tracking errors averaged 0.54° and 0.80°, whereas yaw error averaged 1.36° and showed persistent bounded oscillations. Static equilibrium showed that the rear rotor had to provide 40.7% of hover thrust, compared with 29.7% for each lateral rotor. A four-rotor fixed vertical layout was therefore designed around the established center of gravity, while the original rear motor was retained horizontally for cruise. The new thrust centroid is only 0.81 mm from the center of gravity and the nominal hover load is approximately 38.01 N per rotor. The redesign is expected to provide more symmetric loading and simpler VTOL control.*

Key Words: *flying-wing UAV, VTOL, tri-rotor, quad-rotor, center of gravity, center of thrust, flight-log analysis, yaw oscillations*

1. INTRODUCTION

Hybrid VTOL unmanned aerial vehicles combine the range and cruise efficiency of fixed-wing aircraft with vertical take-off, landing, and hover capability. They are therefore suitable for surveillance, mapping, inspection, and emergency-response missions where runway independence is required, although this versatility increases mechanical and control complexity [1-3].

Flying-wing configurations provide a compact and aerodynamically efficient airframe, but the absence of a conventional tail increases sensitivity to center-of-gravity position, actuator placement, and control coupling. During low-speed VTOL operation, aerodynamic surfaces are weak and attitude control depends mainly on propulsion. Tilt-rotor and tri-rotor concepts consequently use thrust magnitude and vector direction to generate the required forces and moments [4-7].

Tri-rotor layouts can reduce propulsion-unit count and mass, but their triangular geometry commonly produces unequal longitudinal moment arms and non-cancelling rotor torques. Tilting mechanisms provide additional control authority, yet introduce servo dynamics, mechanical tolerances, and axis coupling. Transition between rotor-supported and wing-supported flight further changes actuator effectiveness and trim, motivating nonlinear and mode-dependent control approaches [8-10].

Rotor position and thrust are related to total force and attitude moments through the control-allocation model. Poor actuator placement can cause unequal nominal loading, limited control reserve, coupling, and saturation.

Experimental and numerical studies show that allocation strategy and actuator limits directly affect tracking, disturbance rejection, and handling qualities in multirotor and distributed-propulsion aircraft [11-18].

A rectangular four-rotor layout can provide more symmetric longitudinal and lateral moment arms than a triangular tri-rotor arrangement. Differential thrust between left-right and front-rear pairs generates roll and pitch moments, while suitable rotation directions reduce residual yaw torque.

Stable tri-rotor flight remains possible, but requires accurate actuator modelling and sustained control effort; handling-quality assessment should therefore consider tracking error, oscillation, and actuator demand, not only loss of control [19, 20].

This study uses three flight logs from a 4.18 m-span, 15.5 kg flying-wing VTOL UAV to relate bounded yaw oscillations and unequal motor commands to the original rotor geometry. Static equilibrium is used to quantify the tri-rotor hover-load distribution, after which a fixed four-rotor VTOL layout is positioned around the established center of gravity. The objective is a practical redesign methodology rather than a complete nonlinear transition model.

Although hybrid VTOL control has been studied extensively, fewer publications use flight-log evidence from a large flying-wing tri-rotor as the direct basis for changing the propulsion geometry.

A controlled flight can remain bounded while still showing weak damping, sustained oscillation, unequal actuator loading, or continuous corrective activity.

These indicators are relevant because they reveal limited control quality before a complete loss of stability occurs.

The contribution of this work is therefore threefold: the available flight data are quantified using attitude errors and actuator signals; the nominal thrust demand of the original rotors is derived from static force and moment equilibrium; and the replacement layout is checked by comparing its thrust centroid with the established aircraft center of gravity. The method deliberately remains concise so that the experimental observations and the engineering redesign can be evaluated within the same framework.

2. EXPERIMENTAL ASSESSMENT OF THE ORIGINAL TRI-ROTOR VTOL CONFIGURATION

The investigated platform is a hybrid flying-wing UAV with a 4180 mm wingspan, a 411.7 mm mean aerodynamic chord, and a 15.5 kg take-off mass. Its center of gravity is located 843.375 mm aft of the nose on the symmetry plane. Figure 1 shows the aircraft in VTOL flight, while Table 1 lists the principal characteristics.



Figure 1 - Investigated hybrid flying-wing UAV during an experimental VTOL flight

Table 1 – Main characteristics of the investigated flying-wing VTOL UAV

Parameter	Value
Aircraft configuration	Hybrid flying-wing VTOL UAV
Wingspan including winglets	4180 mm
Approximate fuselage length	1263 mm
Mean aerodynamic chord	411.7 mm
Take-off mass	15.5 kg
Longitudinal CG position from nose	843.375 mm
Lateral CG position	0 mm
Original number of VTOL rotors	3
Motor model	T-Motor MN805-S KV170
Supply voltage	50.4 V

The original system comprised two lateral tilting rotors ahead of the center of gravity and one rear tilting rotor on the symmetry axis. Relative to the center of gravity, the left and right rotors were located at $(-319.53, -1548.8)$ mm and $(-319.53, +1548.8)$ mm, and the rear rotor at $(+466.36, 0)$ mm. The x-axis was positive aft and the y-axis positive toward the right wing (Figure 2).

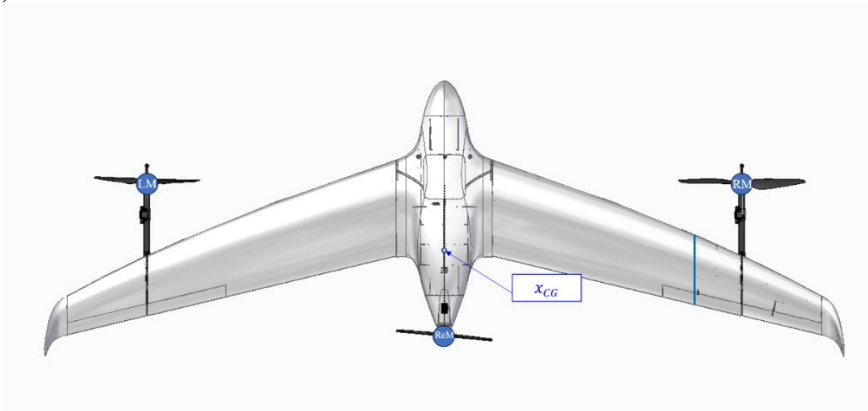


Figure 2 - Original tri-rotor geometry and center of gravity

All units used T-Motor MN805-S KV170 motors. The lateral rotors used G26×8.5 propellers, whereas the rear unit used an Aeronaut CAMcarbon 18.5×12 folding propeller. The left propeller rotated clockwise and the other two counterclockwise. All motors operated during VTOL; during transition the lateral motors stopped and the rear unit provided forward thrust.

Three VTOL flights were analysed. Their durations were 93.7, 70.8, and 76.5 s, with maximum altitudes of 10.38, 9.15, and 8.20 m. The logs contained commanded and measured attitude, motor and servo PWM, altitude, and vibration indicators (Table 2). No complete transition to wing-borne flight was available.

Before the flight campaign, ground tests were performed to verify the operation of the propulsion system, the vectoring mechanisms, the control surfaces, the onboard sensors, and the communication with the ground station.

The accelerometers, gyroscopes, magnetometer, radio receiver, motor commands, and servo outputs were calibrated. The neutral positions and travel limits of the control surfaces and tilting mechanisms were also checked. Propulsion-system tests were initially conducted without propellers and were subsequently repeated with the complete motor-propeller assemblies installed. These tests confirmed the continuity of the control chain from the autopilot outputs to the motor and servo responses.

The altitude and pressure histories displayed the expected inverse relationship between the two quantities. The increase in altitude during take-off and climbing was accompanied by a reduction in barometric pressure, while the descent toward the landing point resulted in a gradual pressure recovery.

These signals confirmed the execution of low-altitude VTOL manoeuvres, but they were not used as direct stability indicators because a commanded-altitude reference was not available in the processed dataset.

Table 2 – Summary of the three analysed VTOL flights

Parameter	Flight 1	Flight 2	Flight 3
Analysed duration, s	93.7	70.8	76.5
Maximum altitude, m	10.38	9.15	8.20
Maximum motor PWM, μ s	1808	1831	1767
Maximum vibration X, m/s^2	3.76	3.34	2.67
Maximum vibration Y, m/s^2	6.86	6.32	5.44
Maximum vibration Z, m/s^2	6.73	4.95	3.71

Attitude tracking was evaluated from the difference between commanded and measured roll, pitch, and yaw angles:

$$e_{\alpha}(t) = \alpha_{\text{cmd}}(t) - \alpha_{\text{meas}}(t). \quad (1)$$

The mean absolute error (MAE) was calculated as

$$MAE_{\alpha} = \frac{1}{N} \sum_{k=1}^N | \alpha_{\text{cmd}}(k) - \alpha_{\text{meas}}(k) |, \quad (2)$$

where N is the number of analysed samples.

Table 3 summarizes the results. Average roll, pitch, and yaw MAE values were 0.54° , 0.80° , and 1.36° , respectively.

Table 3 – Mean absolute attitude-tracking errors

Flight	Roll MAE, °	Pitch MAE, °	Yaw MAE, °
Flight 1	0.50	0.69	1.45
Flight 2	0.58	0.73	1.39
Flight 3	0.55	0.97	1.25
Average	0.54	0.80	1.36

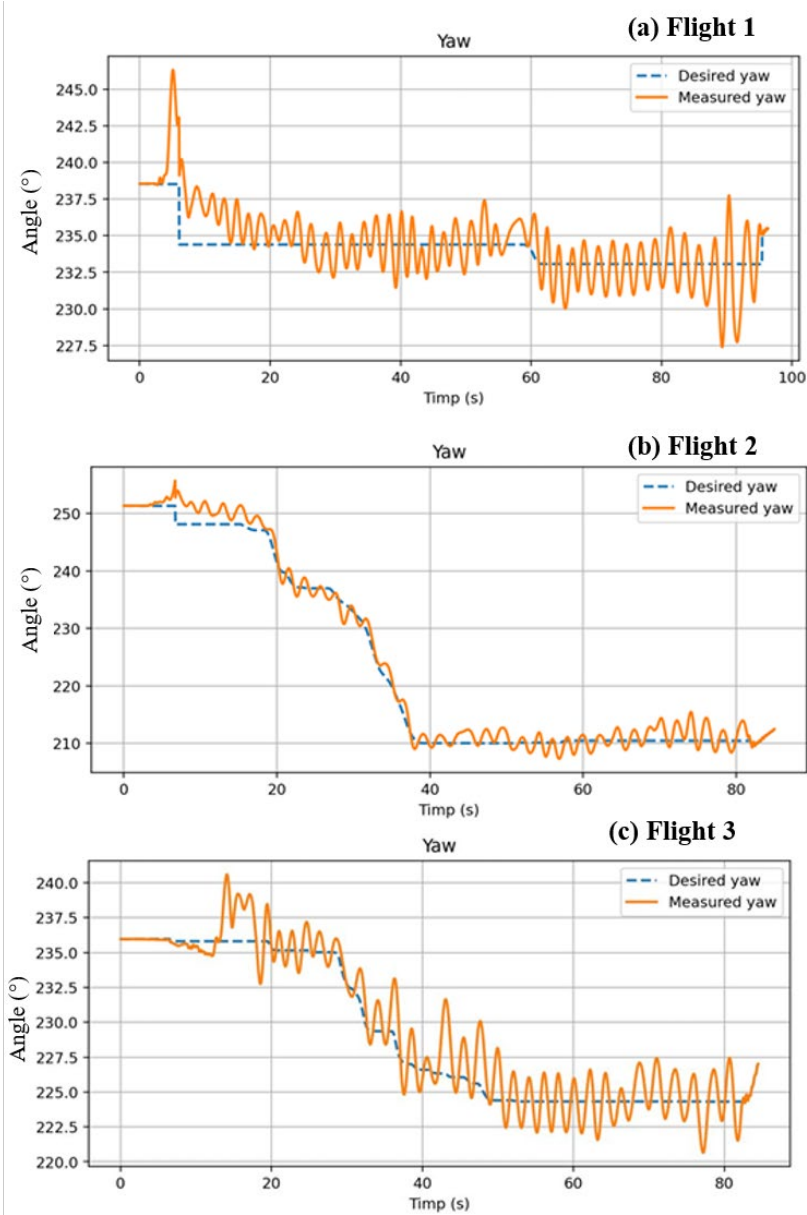


Figure 3 - Commanded and measured yaw angles during the three analysed VTOL flights: (a) Flight 1; (b) Flight 2; and (c) Flight 3

Roll and pitch generally followed their commands closely, whereas yaw exhibited persistent bounded oscillations in all three flights (Figure 3).

The mean yaw error was approximately 2.5 times the roll error and 1.7 times the pitch error. The response remained controllable, but the repeated oscillation indicates lower directional damping or greater corrective demand rather than divergent instability.

The recurrence of the yaw pattern in all three flights makes a single isolated disturbance an unlikely explanation. Possible contributors include the unequal longitudinal rotor arms, the unmatched reaction torques associated with one clockwise and two counterclockwise propellers, the different rear-propeller characteristics, and the dynamic response of the tilting mechanisms.

The available data do not separate these effects completely, but they establish a repeatable directional-control limitation relevant to the redesign.

The left and right motor commands remained similar, while the rear motor consistently operated at higher PWM.

Because the rear unit used a smaller propeller, PWM cannot be interpreted directly as thrust; nevertheless, the pattern indicates a higher rear-unit demand. The lateral vectoring servos also showed continuous corrections, whereas the rear servo remained nearly constant. The recorded motor and servo signals are shown in Figure 4.

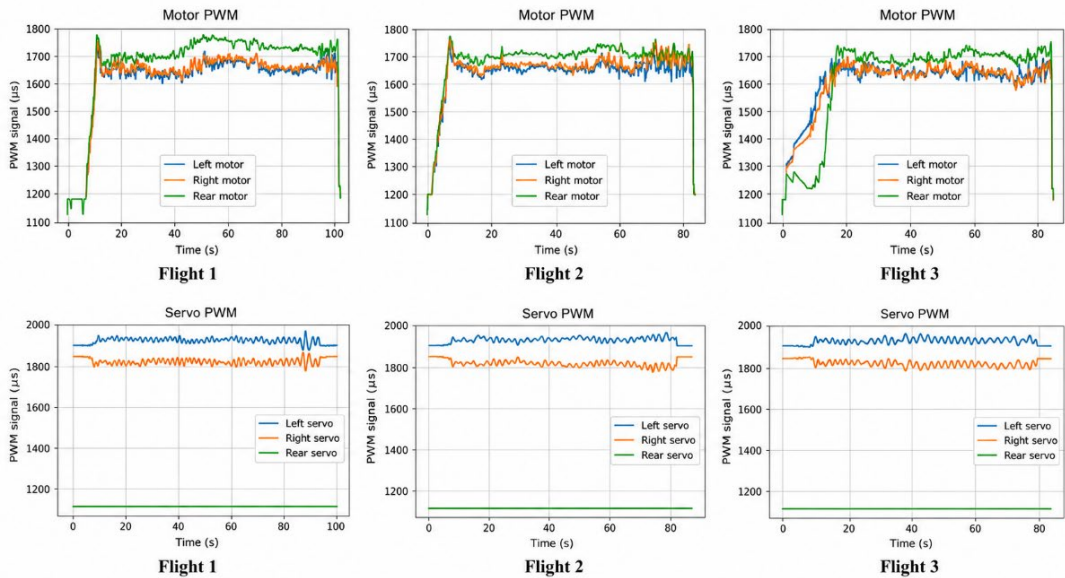


Figure 4 - Motor and thrust-vectoring servo PWM signals recorded during the three experimental VTOL flights: (a, b) Flight 1; (c, d) Flight 2; and (e, f) Flight 3

Vibration remained low in all tests. Maximum Y-axis values were 6.86, 6.32, and 5.44 m/s^2 , well below the 15 m/s^2 reference threshold (Figure 5). Severe broadband vibration was therefore unlikely to be the main cause of the yaw oscillations, although the processed data do not exclude local structural or frequency-specific effects.

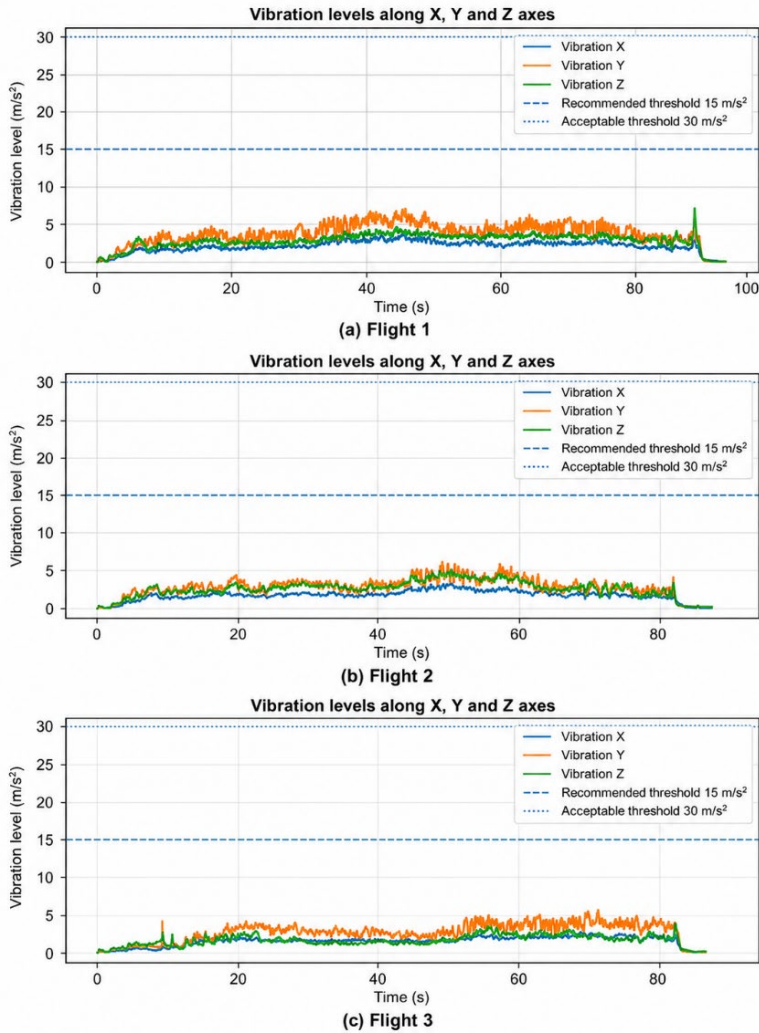


Figure 5 - Vibration levels recorded along the X, Y, and Z axes during: (a) Flight 1; (b) Flight 2; and (c) Flight 3. The dashed lines indicate the recommended and acceptable reference thresholds

The flights therefore show a bounded but asymmetric VTOL operating condition: yaw tracking was poorer than roll and pitch, the rear motor had the highest command demand, and the vectoring servos remained active. These observations motivate the following static comparison of the original and redesigned rotor layouts.

3. ANALYTICAL REDESIGN AND COMPARATIVE EVALUATION OF THE VTOL PROPULSION LAYOUT

A simplified hover model was used to compare both layouts. Vertical thrust was assumed perpendicular to the aircraft plane, while rotor-wing interaction, structural deformation, actuator transients, and vertical rotor-plane offset were neglected. The local origin was the aircraft center of gravity, $XCG = 843.375$ mm from the nose and $YCG = 0$; x was positive aft and y positive to the right.

The original rotor coordinates relative to this origin are given in Table 4.

Table 4 – Rotor coordinates of the original tri-rotor configuration relative to the aircraft center of gravity

Rotor	x, mm	y, mm
Left Rotor	-319.53	-1548.8
Right rotor	-319.53	+1548.8
Rear Rotor	+466.36	0

In ideal hover, total vertical thrust balances the aircraft weight:

$$T_L + T_R + T_T = mg, \quad (3)$$

where T_L , T_R , and T_T are the left, right, and rear thrusts. Lateral symmetry gives

$$T_L = T_R = T_F.$$

For the 15.5 kg aircraft,

$$W = mg = 15.5 \times 9.81 = 152.055 \text{ N}.$$

Zero pitch moment requires the two forward-rotor moments to balance the rear-rotor moment:

$$2(319.53)T_F = 466.36T_T.$$

Solving the force and moment equations gives

$$T_L = T_R = 45.12 \text{ N},$$

and

$$T_T = 61.82 \text{ N}.$$

Thus, each lateral rotor carries 29.67% of the weight, while the rear rotor carries 40.66% and produces about 37% more thrust. Equal rotor thrust would place the thrust centroid 57.57 mm ahead of the center of gravity. These results agree with the higher rear-motor PWM observed in flight.

The PWM ratio is not a direct thrust ratio because the rear propeller differs from the lateral propellers. In addition, one clockwise and two counterclockwise rotors do not cancel reaction torque naturally. The combination of unequal loading, different propellers, and thrust vectoring therefore provides a plausible explanation for the increased yaw-control effort.

The redesign uses four identical fixed vertical MN805-S KV170/G26×8.5 units in a nearly rectangular layout. The original lateral motors are reused at the front positions and two identical units are added at the rear. The original rear motor remains fixed horizontally for cruise and is excluded from VTOL force allocation.

The proposed vertical-rotor coordinates are listed in Table 5.

Table 5 – Rotor coordinates of the proposed four-rotor VTOL configuration relative to the aircraft center of gravity

Rotor	x, mm	y, mm
Front-left rotor	-842.62	-1548.8
Front-right rotor	-842.62	+1548.8
Rear-left rotor	+841.00	-1549.3
Rear-right rotor	+841.00	+1549.3

For equal vertical thrust, the proposed rotor centroid is $x_T = -0.81 \text{ mm}$ and $y_T = 0$ relative to the aircraft center of gravity.

The 0.81 mm longitudinal offset is only about 0.20% of the mean aerodynamic chord and is negligible for this analysis.

At the reference mass of 15.5 kg, each vertical rotor must generate approximately 38.01 N (3.88 kgf), corresponding to 25% of the total hover load.

Because the front and rear longitudinal moment arms are not exactly equal, the precise pitch-balanced thrusts can also be calculated. Let the thrust generated by each front rotor be T_F^{4R} , and that generated by each rear rotor be T_R^{4R} . Vertical-force equilibrium requires

$$2T_F^{4R} + 2T_R^{4R} = W,$$

while pitch-moment equilibrium gives

$$2(842.62)T_F^{4R} = 2(841.00)T_R^{4R}.$$

The resulting values are

$$T_F^{4R} = 37.98 \text{ N}$$

for each front rotor and

$$T_R^{4R} = 38.05 \text{ N}$$

for each rear rotor. The difference between the front and rear thrusts is only approximately 0.07 N and can be neglected in practical hover operation. The configuration can therefore be treated as having an equal nominal load of approximately 25% of the aircraft weight on each vertical rotor.

Manufacturer data indicate that this thrust level is close to the 42% throttle operating point of the selected motor-propeller combination, leaving substantial static-thrust reserve.

The equal loading of the four vertical propulsion units also produces a more symmetric moment-generation mechanism. The simplified total vertical thrust is

$$T_\Sigma = T_{FL} + T_{FR} + T_{RL} + T_{RR}.$$

The roll moment can be generated by varying the combined thrust on the left and right sides:

$$L \approx b[(T_{FR} + T_{RR}) - (T_{FL} + T_{RL})],$$

where b represents the average lateral rotor distance from the center of gravity.

Similarly, the pitch moment can be generated by varying the combined thrust of the front and rear rotor pairs:

$$M \approx x_R(T_{RL} + T_{RR}) - x_F(T_{FL} + T_{FR}).$$

In the original tri-rotor configuration, the centerline rear rotor did not provide a direct roll moment because its lateral coordinate was zero. Roll control depended primarily on the thrust difference between the two lateral motors. In the proposed arrangement, all four vertical motors contribute to the available roll control through their lateral moment arms. Pitch control is similarly divided between two front and two rear propulsion units instead of relying on a single highly loaded rear unit.

The use of identical motors and propellers also simplifies the relationship between motor command and generated thrust. In the original arrangement, the different rear propeller prevented a direct comparison between the PWM commands of the three rotors. In the proposed architecture, all four vertical propulsion units have the same motor-propeller

combination, so approximately equal PWM commands are expected to generate approximately equal thrusts under comparable operating conditions.

The replacement of the tilting VTOL units with fixed vertical propulsion units further reduces the number of continuously active mechanical degrees of freedom during hover. The original system required repeated vectoring-servo corrections, whereas the proposed system generates roll and pitch moments primarily through differential thrust.

This does not eliminate the need for suitable controller tuning, but it removes servo dynamics, mechanical backlash, and vectoring-position uncertainty from the primary VTOL stabilization mechanism.

Table 6 summarizes the principal differences between the two configurations.

Table 6 – Comparison of the original and proposed VTOL propulsion configurations

Parameter	Original configuration	Proposed configuration
VTOL rotor orientation	Tilting	Fixed vertical
VTOL motor model	MN805-S KV170	MN805-S KV170
VTOL propellers	Two G26×8.5 and one 18.5×12	Four G26×8.5
Equal-thrust centroid relative to CG	−57.57 mm	−0.81 mm
Left/lateral thrust	45.12 N	Approximately 38.01 N
Maximum nominal rotor thrust	61.82 N	Approximately 38.05 N
Maximum individual hover-load share	40.66%	Approximately 25%
Nominal thrust distribution	Unequal	Approximately equal
Main roll-control source	Difference between lateral rotors	Difference between left and right rotor pairs
Main pitch-control Source	Lateral pair versus rear rotor	Front pair versus rear pair
Number of vertical VTOL rotors	3	4
Mechanical vectoring during VTOL	Required	Not required
Rear cruise motor	Also used during VTOL	Fixed horizontally and excluded from VTOL

The redesign reduces the maximum nominal rotor share from 40.66% to about 25% and places the equal-thrust resultant practically through the established center of gravity. It therefore provides a more uniform operating point and greater relative reserve for corrective thrust.

From a control-authority perspective, the reduction in nominal rotor loading is important because corrective manoeuvres depend on the thrust margin remaining above the hover operating point. In the original layout, the rear unit already carried more than 40% of the aircraft weight, leaving a smaller relative increase available before reaching the motor-propeller limit. In the proposed layout, each vertical unit begins near one quarter of the total load, so roll and pitch corrections can be distributed between rotor pairs instead of being concentrated on a single rear actuator. This does not guarantee improved closed-loop stability by itself, but it provides a more favourable allocation geometry for controller tuning.

The fixed four-rotor arrangement also separates the propulsion functions more clearly. The four vertical units are dedicated to take-off, hover, and landing, whereas the original rear unit is retained horizontally for cruise propulsion. Such separation avoids the continuous change in thrust-vector orientation required by the previous architecture and reduces sensitivity to servo backlash, calibration differences, and actuator-rate limitations. The use of

the same motor and propeller on all vertical stations further improves command consistency and makes future thrust calibration easier.

The redesign nevertheless introduces practical penalties. Two additional vertical propulsion units increase mass, electrical demand, structural loads, and potential rotor-wing interference. These effects were outside the available dataset and should be evaluated after detailed structural integration. The present comparison therefore identifies the geometric and static-equilibrium advantages of the proposed layout, while recognising that final performance will also depend on the redesigned mass, power system, aerodynamic interaction, and controller parameters.

The calculation aligns the center of thrust with the existing center-of-gravity reference; it does not prove that the complete physical center of gravity remains unchanged after adding motors and supports.

The final aircraft may also be heavier than 15.5 kg. Rotor interference, structural flexibility, motor dynamics, and detailed yaw allocation were not modelled, and the proposed configuration still requires experimental validation.

A distinction must be maintained between center of thrust and physical center of gravity. The present calculation proves that the resultant hover thrust of the proposed four vertical rotors acts practically through the previously established center-of-gravity reference. It does not include a complete mass-moment balance for the added motors, mounts, wiring, and structural reinforcement. After construction, the final center of gravity should therefore be measured and any small deviation corrected by relocating onboard components.

The comparison also retains the 15.5 kg reference mass to isolate the influence of rotor geometry. If the redesigned aircraft is heavier, the absolute thrust required from each rotor will increase, but the approximately equal 25% load fraction and the calculated thrust-centroid position will remain consequences of the selected geometry.

Additional limitations include the neglect of rotor aerodynamic interference, propeller slipstream interaction with the wing, structural flexibility, wind disturbances, motor-response dynamics, and detailed yaw-torque allocation.

Furthermore, the proposed configuration has not yet been evaluated through flight testing. The calculated improvements should therefore be interpreted as expected benefits based on static equilibrium and geometric symmetry rather than as experimentally demonstrated improvements.

A practical validation campaign should begin with individual thrust measurements for the selected motor-propeller units and a verification of the complete aircraft mass and center of gravity. Tethered or restrained hover tests can then be used to check motor-command symmetry, available thrust reserve, and the absence of structural interference before free flight. These steps would also provide the thrust-command relationship needed for a more detailed control-allocation model.

Free-flight validation should reproduce the manoeuvres used in the present dataset and compare attitude MAE, peak yaw deviation, motor-command spread, and vibration levels. Demonstrating lower directional oscillation and more uniform rotor commands under comparable conditions would provide the experimental evidence required to confirm the analytical benefits of the four-rotor layout.

Within these limits, the analysis links the observed tri-rotor asymmetry to a practical four-rotor solution expected to simplify VTOL control and improve robustness.

4. CONCLUSIONS

This study evaluated three VTOL flights of a 4.18 m-span, 15.5 kg flying-wing UAV equipped with three tilting propulsion units. The aircraft remained controllable, with average roll, pitch, and yaw errors of 0.54° , 0.80° , and 1.36° , respectively. Yaw nevertheless displayed persistent bounded oscillations and the rear motor operated at a consistently higher PWM level, while the recorded vibration indicators remained below the adopted reference thresholds.

Static equilibrium showed that the original triangular geometry required 45.12 N from each lateral rotor and 61.82 N from the rear rotor. The corresponding hover-load shares were 29.67%, 29.67%, and 40.66%, so the rear unit had to produce approximately 37% more thrust than either lateral unit. This result provides a direct analytical explanation for the asymmetric nominal operating condition observed in the flight logs.

The proposed architecture uses four identical fixed vertical MN805-S KV170/G26 $\times$ 8.5 propulsion units, while the existing rear motor is retained horizontally for forward flight. The calculated thrust centroid is only 0.81 mm from the established center of gravity, and the nominal hover requirement is approximately 38.01 N per vertical rotor. The maximum individual load share is therefore reduced from 40.66% to about 25%.

The redesigned arrangement is expected to provide a more uniform actuator operating point, greater relative thrust reserve, and simpler roll and pitch control through differential thrust. It also removes tilting-servo dynamics and propeller mismatch from the primary VTOL stabilization mechanism. The experimental data support the need for the redesign, but they do not constitute flight validation of the new architecture.

Future work should verify the final physical center of gravity after installation, perform ground thrust tests, and repeat the same VTOL manoeuvres with the four-rotor layout. Comparative evaluation should use the same attitude-error, PWM, servo-activity, and vibration indicators so that the predicted improvements can be assessed under equivalent conditions.

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